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MECHATRONICS DESIGN OF A ROBOT SOCIETY

- A Case Study of Minimalist Underwater Robots for Distributed Perception and Task Execution

Pekka Appelqvist

Dissertation for the degree of Doctor of Technology to be presented with due permission for public examination and debate in Auditorium T2 at Helsinki University of Technology (Espoo, Finland) on the 17th of November 2000, at 12 o'clock noon.

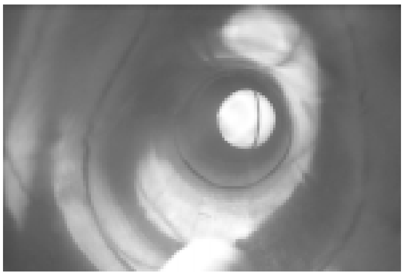

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Photo on the title page: SUBMAR robot travelling in a water pipe.

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Abstract

This thesis describes the mechatronics design of a cooperative multi-robot system, including systems level design, practical implementation, and testing. Two main subjects are integrated in this research work: the generic concept of a Robot Society as an engineering framework to control an autonomously operating distributed multi-robot system, and the constructed prototype society consisting of several sensor/actuator robots for submerged use in a liquid environment.

These novel types of prototype robots, SUBMARs, are targeted for distributed autonomous perception and task execution in the internal, three-dimensional on-line monitoring of various flow-through processes. The Robot Society control architecture implemented into SUBMAR robots supports such features as the autonomous cooperation of the robots, multi-tasking, self-organization, and self-optimization in task execution. The mechatronics design of the robots has followed a minimalist approach, where the structure of the robot is maximally simplified. As a solution to compensate the obvious limitations derived from minimalism, the multiplicity and the cooperation of the robots have been exploited. On a systems level, this produces fault tolerant, flexible, and cost-effective engineering solutions for application.

Altogether over 90 logged experiment runs with physical robots have been completed to elucidate the functioning and reveal the factors affecting the performance of the system. The testing has been performed in a laboratory environment in a special demonstration process. In these experiment series, the searching and destroying of distributed dynamic targets were tested. Furthermore, the meaning of communication in the development of robot consciousness during the mission has also been analyzed.

As a result of the research work and systems development, profound knowledge has been gained and new solutions presented for the required technology for a minimalist mobile robot operating in a liquid process environment. SUBMAR Robot Society forms a technological basis for the development of real-world applications in the future.

Keywords: Multi-robot systems, robot society, mechatronics design, underwater robots, minimalist approach, robot cooperation, robot consciousness

Preface

This study concerning autonomous mobile multi-robot systems has been carried out at the Automation Technology Laboratory of the Helsinki University of Technology under various research projects from 1995-2000. These projects have been funded mainly by the National Technology Agency (TEKES) and Academy of Finland, which are thereby greatly acknowledged.

Since I graduated in 1996, my full-time research work was ensured by several grants from the Helsinki University of Technology, Tekniikan Edistämissäätiö, the Finnish Society of Automation, and Automation Foundation. Furthermore, in 1999 I was accepted into the national GETA program (the Graduate School in Electronics, Telecommunications, and Automation) to finalize my post-graduate studies. Thus, I would like to thank all these sources for their valuable financial support.

I wish to express my gratitude to *Professor Aarne Halme*, who as the head of the Automation Lab and my supervisor has guided me through the demanding research process. His expertise and advise have been essential during the study.

I am also especially thankful to my co-worker, *Dr. Mika Vainio*. He originally introduced me to the exciting world of behavior-based mobile multi-robot systems and set an example of how to proceed in the academic world. His input for the systems development of the SUBMAR Robot Society has been of the utmost importance; without him, the system would not be operational.

I would like to extend my thanks to all the people who have been involved in this research process: at the early phase, our research group was enriched with professional skills and innovations by *Yan Wang*, *Pekka Kähkönen*, and *Torsten Schönberg*. *Tommi Tuovila* and *Antti Matikainen* invested a great effort in the simulator studies, while *Markku Kontio* and *Sami Ylönen* have contributed to the robots' software development. *Johanna Nikkinen* and *Anja Ranta* have had their share of various phases in the research projects, as in analyzing the test results. *Kalle Rosenblad* has been a trustworthy problem solver in complex electronics matters. Mechanical design and implementation have been assisted by *Tapio Leppänen* and *Markku Viljakainen*, while *Jorma Selkäinaho* and *Ari Kokkonen* have guaranteed smooth running of our computing facilities. In fact, almost all have helped me in some way during the study, so many thanks to *the entire staff of Automation Lab* for creating a friendly, fun, and innovative spirit in our workplace. As well, I wish to acknowledge *Antti Hakala* (Sofimation Oy) and *Tomi Hänninen* (RTD Scandinavia Oy) for their vital credits in the design of the SUBMAR robots.

Furthermore, I extend thanks to my preliminary examiners *Dr. Hajime Asama* and *Professor Raimo Sepponen* for their reviews and valuable comments on the thesis. Many thanks are also due to *Kathleen Tipton* for the language revision of my manuscript.

Finally, I would like to thank *my parents* and *all my good friends* for their support and encouragement throughout the project. I feel so happy to complete my post-graduate studies after some four and a half years of intensive research work! From now on, I should have a life as well, but I am sure it is cool to be a doc…

Otaniemi, Espoo
September 2000 *Pekka Appelqvist*

Contents

List of symbols and abbreviations

A	biomass
c	confidence value
D	death rate of biomass
λ	learning rate
μ	growth rate of biomass
μTAS	micro Total Analysis System
3D	three-dimensional
AC	Alternating Current
A/D	Analog-to-Digital
AI	Artificial Intelligence
AMR	Autonomous Mobile Robot
APN	Adaptive Place Network
ASCII	American Standard Code for Information Interchange
ASIC	Application Specific Integrated Circuit
AUV	Autonomous Underwater Vehicle
CBM	Common Basic Map
CCD	Charge-coupled Device
CEBOT	Cellular Robotic System
CMOS	Complementary Metal Oxide Semiconductor
CPU	Central Processing Unit
CRC	Cyclic Redundancy Check
CSMA/CD	Carrier Sense Multiple Access with Collision Detection
DARS	Distributed Autonomous Robotic Systems
DC	Direct Current
DIP	Dual In-line Package
DSP	Digital Signal Processing
EEPROM	Electrically Erasable PROM
EMC	Electromagnetic Compatibility
FET	Field-Effect Transistor
FSA	Finite State Automata
GPS	Global Positioning System
HUT	Helsinki University of Technology
IDC	Intelligent Data Carrier
IMU	Inertial Measurement Unit
I/O	Input/Output
IR	Infrared
IRC	Inter-Robot Communication

LED	Light Emitting Diode
LIGA	Lithographie, Galvanoformung, Abformung –technology; German for lithography, electroforming, molding
MEMS	MicroElectroMechanical Systems
MOSFET	Metal-Oxide-Semiconductor FET
MST	MicroSystem Technology
NiMH	Nickel Metal Hydride
ORC	Operator-to-Robot Communication
PROM	Programmable ROM
RAM	Random-Access Memory
RF	Radio frequency
ROM	Read-Only Memory
ROV	Remote Operated Vehicle
RS	Robot Society
SRAM	Static RAM
STD	Standard deviation
SUBMAR	Smart Underwater Ball for Measurement and Actuation Routines
UHF	Ultra-High Frequency
URV	Underwater Robotic Vehicle
UUV	Unmanned Underwater Vehicles
UV	Ultraviolet

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and dedicated to white noise.

Chapter 1

Introduction

1.1 Overview

This thesis deals with the mechatronics design of an experimental cooperative multi-robot system, including systems level design, practical implementation, and testing. Two main subjects are integrated in the research work: *the generic concept of the Robot Society* as an engineering framework and control architecture to control an autonomously operating cooperative mobile multi-robot system, and the constructed prototype society consisting of several *mobile sensor/actuator robots for submerged use* in a liquid environment.

As a research field, *cooperative multi-robot systems* is a relatively new area of science. Based on the previous research on mobile robotic platforms and simulator studies on autonomous, AI-inspired agents in the 1980s, the interest in multi-robot systems started to grow and expand rapidly at the beginning of the 1990s. Maybe the time has not come yet, or the technological premises do not exist yet, but at least so far, a unified or well-established theory for a *control architecture* to control a cooperative multi-robot mission has not been formed. Therefore, research in this field has been very experimental by nature.

The scope of potential applications for various multi-robot systems is enormously wide, covering duties from everyday human life to micro-scale manufacturing and distant extra-terrestrial planetary missions. Dozens of approaches have been introduced by leading robotics laboratories and research groups around the world as control architectures for cooperative multi-robot systems. Many of the proposed systems have remained more or less as theoretical simulator studies only, although practical evaluation with respective physical embodiment has proven highly important. Practical limitations in perception, communication, mobility, etc. encountered by the robots in the dynamic real-world environment have proved many good ideas to be technologically infeasible.

Cooperative multi-robot systems cover a wide range of scientific and technological aspects. To name a few key areas for these systems, the *autonomous functioning, cooperation, self-organization, distributed perception,* and *distributed control* of robots have to be mentioned. As can be seen, advanced multi-robot systems turn out as a truly multi-disciplinary research area.

The required features for the intelligent behavior of the robots are all derived from the control architecture, which has to be understood rather as a program structure than as any specific part of the software. The control architecture should support parallel execution of several program processes at a low level (e.g. sensor sampling or communication) and tasks at a high level (e.g. navigation or optimization of performance). The structure of the control architecture can be generic by nature to a certain extent, but the connections to inputs (sensors) and outputs (actuators) attach the architecture to the application. Due to the complex system requirements, thoroughgoing *systems level analysis and design* is an essential process before moving on to the actual software and hardware design of the robots. For example, detailed attention should be paid to the implementation of the user interface and safety features already at the systems level design phase.

Mechatronics is an essential technology to the realization of a robotic system. In this context, mechatronics is understood in its most intelligent and advanced meaning. Today's advanced mechatronics integrates *mechanics, electronics,* and *embedded software*. In many cases, due to the integrated nature of the design, the functioning of these elements can no longer be clearly separated. Instead, mechanics, electronics, and software augment each other, producing a functional value greater than their sum alone. Autonomous mobile robots are concrete and illustrative examples of advanced mechatronics devices.

Technological minimalism is another key aspect throughout this thesis; concerning the entire mechatronics design process, maximally reduced and simplified, but still functional and robust solutions have been sought. The limitations of this minimalist approach are compensated for with the multiple and cooperative use of robots. A minimalist design scheme promotes reliable and cost-effective solutions prepared for mass production.

When multi-robot research was just underway at the HUT Automation Technology Laboratory in the early 1990s, various suitable platforms were considered to test the ideas related to cooperative multi-robot behavior and control. In this context, the idea of the so-called *bacterium robot society* (discussed in Section 3.2) was developed based on the concept of the Robot Society, see [Halme et al., 1993]. In the following year, 1994, these thoughts led to a research project, which aimed at setting up a fully operational demonstration system of a bacterium robot society to allow multi-robot studies with physical robots.

The demonstration society consists of several cooperative robots members. For these purposes SUBMAR (Smart Underwater Ball for Measurement and Actuation Routines) robots were developed. These are mobile autonomous sensor/actuator platforms intended for the 3D internal monitoring and controlling of liquid processes. These underwater robots are designed by strictly following the minimalist approach, which, for instance, results in underactuated maneuverability and only rough areal positioning capabilities in this case. In a real-world application, the SUBMAR type of sensor/actuator robots could augment standard fixed process instrumentation and operate as a part of the automation system by controlling certain tasks in flow-through processes. In Figure 1.1, the main functional features of the developed system are illustrated, while Figure 1.2 shows the physical embodiment of the bacterium robot society in action.

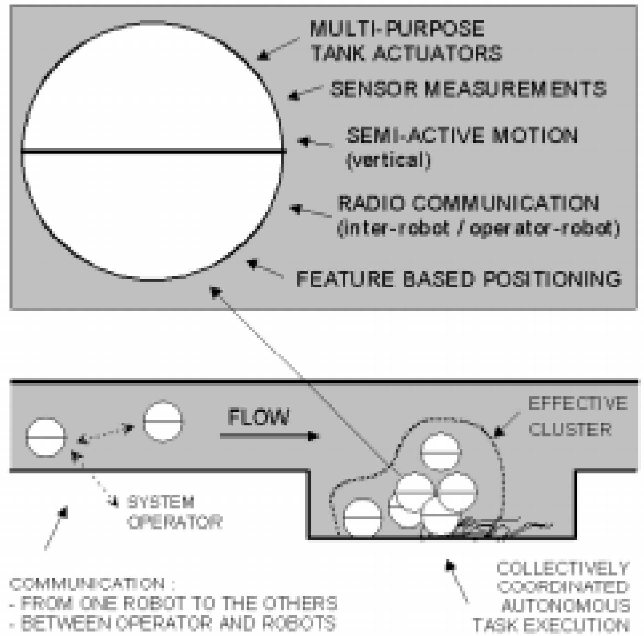


Figure 1.1 *Main functional features of the SUBMAR Robot Society.*

Figure 1.2 *The demonstration system in action: three SUBMAR robots are visible in the background.*

1.2 Motivation and aims for the study

The motivation for the study behind this thesis was to research, develop, and analyze the technology required for the novel breed of mobile underwater robots along with multi-robot studies in a new environment. In the mechatronics development process of SUBMAR robot prototypes, new solutions were innovated while characteristics from various types of robotic devices and intelligent instrumentation were combined. However, the ultimate aim was to set up a prototype series of SUBMAR robots to enable practical multi-robot studies with Robot Society architecture in a 3D laboratory test environment. Research work for this thesis has been carried out as a hands-on study to present a practical engineering point of view on the subject.

Concerning the systems design and mechatronics design processes, the following problems and questions in particular have been addressed by means of a case study:

- What are the technological premises for a minimalist approach to create a distributed robotic system in an underwater environment?
- How can simple robot units be turned into a system capable of coping with complex missions and multi-tasking?
- How to implement the self-organizing and self-optimizing structures of these robots?
- How to promote cooperation in simple interactions between robots?
- What mechanisms are needed in the communication structure?
- What factors affect the dynamics of the distributed multi-sensor perception and robot consciousness?

1.3 Scientific contribution of the dissertation

The scientific contribution of this dissertation consists of the following themes:

- A novel mobile sensor/actuator robot -concept for the submerged use of various liquid flow-through processes has been introduced. The mechatronics structure of minimalist and modular SUBMAR robot prototypes has been described in detail including mechanics, electronics, and software solutions. Related technology and potential applications have also been surveyed.
- The concept of the Robot Society as a systems-level framework to control a multi-robot mission has been formulated and presented from an application-oriented engineering point of view.
- A great deal of attention was given to the practical implementation of the complex system. As a result of this research work, the prototype system has

matured yielding ideas on how to combine robotics and the process industry in automation systems monitoring liquid processes in 3D, in the future.

- The functioning of the unique SUBMAR society was analyzed with extensive testing with the actual robots in a laboratory test environment. The performance of the system was evaluated using a "search and destroy" –type of task, where the robots performed against emulated dynamic targets. The development of robot consciousness and the collective consciousness of the whole society was also studied during the task execution. As far as is known, this has been the first distributed and cooperative multi-robot system demonstration in a 3D-environment.

1.4 Outline of the dissertation

The chapters of this dissertation are organized as follows:

Chapter 1: *Introduction.* A short introduction to the research subjects of the thesis.

Chapter 2: *Autonomous robotic systems and mobile instrumentation.* Various robot categories, multi-robot systems, and some novel approaches for mobile instrumentation relevant to the scope of the thesis are reviewed.

Chapter 3: *Applying the concept of the Robot Society.* In this chapter, Robot Society and its control architecture are discussed as an engineering concept. The experimental platform, minimalist underwater robots, SUBMARs, are introduced.

Chapter 4: *Mechatronics structure of SUBMAR robots.* This chapter consists of a detailed description and analysis of the mechanics, electronics, and software solutions developed for SUBMAR robots.

Chapter 5: *Experiments with the SUBMAR society.* The test environment, task definition, and results from the two experiment series to verify and analyze the functioning of the SUBMAR society are presented in this chapter. In the first series of experiments, the searching and destroying of distributed dynamic targets were tested. The second series was performed to analyze the meaning of communication in the development of robot consciousness during the mission.

Chapter 6: *Technological considerations.* The technological feasibility of various enhancements for the SUBMAR-type of robot, as well as potential applications for such robots, are discussed in this chapter.

Chapter 7: *Conclusions.* Summary of the research and conclusions along with suggestions for future work is presented in the last chapter.

1.5 Author's contribution within the research group

The research work documented and presented in this thesis was carried out from 1995-2000 in a dynamic research group. For a short period, this group had up to seven members, although most of the time there have been just two or three persons in the research group. The author's main scientific contribution to the group has been in the systems level design of the SUBMAR Robot Society, concerning, for example, the communication systems design and the robots' task design. Furthermore, the author has been responsible for the robots' mechatronics implementation, including electronics, software, and mechanics design.

Robot Society control architecture and many high-level software features, such as the environment mapping and navigation system, were mainly developed by Dr. Mika Vainio. His doctoral dissertation serves as a comprehensive documentation of those issues. Due to the tight connection between these two theses, [Vainio 1999] is referred to frequently.

The test results presented in Experiment Series I (Section 5.3) were performed together with Dr. Vainio, while the results in Experiment Series II (Section 5.4) were performed solely by the author.

Chapter 2

Autonomous robotic systems and mobile instrumentation

2.1 Introduction

This chapter outlines the research field concerning the concepts of *the Robot Society* and *the sensor/actuator robot*. The background for both concepts is very cross-technical, multi-disciplinary, and versatile by nature.

The overview begins with a short review of the evolution and classification of autonomous mobile robots. Certain specific types of robot are then discussed: underwater robots and in-pipe robotic vessels. This is followed by an introduction to reactive robot control and minimalist philosophy in robotics, which leads to the research of distributed cooperative multi-robot systems.

Along with the general development of microprocessors and embedded processing capacity, wireless data communications systems, and sensor technology, different technical devices and machines have become increasingly intelligent. This development has allowed greater autonomy, spatial distribution, and mobility for many devices. As a result, the difference between robots and various types of intelligent machines or devices is narrowing down continuously. A few examples of this development are reviewed as well.

2.2 Autonomous mobile robots

Autonomously operating mobile robots have fascinated people for decades. The stereotypic concept of what the ultimate general purpose *robot* should do and look like has changed relatively little from 1950s sci-fi films where, for example, the famous anthropomorphic Robby the Robot obediently served his master, Dr. Morbius, on the distant planet Altair IV (Forbidden Planet, MGM, 1956). It has always been expected that a robot could move among people to serve us, or replace man in difficult and dangerous environments. Despite continuously increasing worldwide interest, developing technology, and extensive research work in the robotics field, the ultimate goal is still a long way ahead. See, for instance, [Rosheim 1994] for a nice presentation of the slow progress in the early evolution of humanoid robots. On the other hand, it has been well understood that in order to be useful, mobile robots do not necessarily have to have very complex structures or share human-like forms. Despite this, truly autonomous mobile robots are still quite a rare sight in industrial or other practical applications.

Since the 1980s, the processing capacity and the sensors needed to control an autonomously moving and navigating robot have become available in a reasonable physical size, and at a relatively low cost. Stationary manipulator robots came of age as a technology in the 80s and established an irrevocable position in industrial manufacturing. As a result, the frontier of robotics research moved towards Autonomous Mobile Robots (AMRs).

A huge number of different, although mainly wheel-based AMRs for various applications have been introduced in the last two decades. Proposed applications range from indoor service robotics to distant planetary missions. The physical size of these robots may vary from heavy mining machinery to a micro-scale insectoid type of robot. For a broad overview of the development of various types of autonomous robotic vehicles in the 1990s, see, for example, the conference series of Intelligent Autonomous Vehicles, [IAV 1993], [IAV 1995], [IAV 1998], or [ARS 1998]. All environments on land, in the air, and under the sea are included. However, flying robots are hard to find. Alternative solutions for wheel-based motion, especially in walking and climbing technology, are well reviewed and classified in [CLAWAR 1999] and [CLAWAR 2000].

Due to the wide spectrum of applications, clear and unambiguous classification of mobile robots is very challenging. For instance, wheeled robots are usually divided into categories depending on their physical size, whereas walking robots are normally classified according to the number of their legs. In Figure 2.1, a rough categorization of the existing types of mobile robot is suggested according to their mode of mobility.

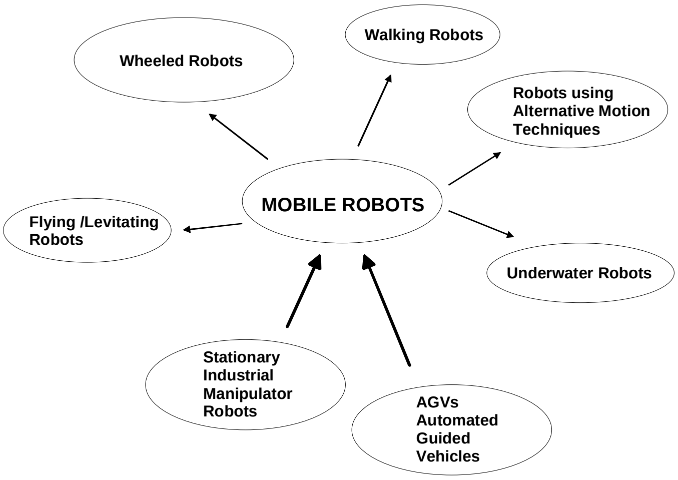


Figure 2.1 *Classification of mobile robots and the preceding main technologies.*

2.2.1 Robots for an underwater environment

A generally used term for any diving robot is Underwater Robotic Vehicle (URV). These underwater robots can be truly Autonomous Underwater Vehicles (AUVs), although the great majority of URVs are actually tethered Remote Operated Vehicles (ROVs), because of the limitations in underwater communication. This type of robot is typically open framed, operated with multiple thrusters, and equipped with manipulator arms, cameras, sonars, and other sensors depending on the level of autonomy of the robot. It is designed for the recovery of sunken ships or wrecked aircraft, underwater construction or maintenance work, and other applications dangerous or impossible for human divers. For an overview of the applied technology in URVs, see, for instance, [IROS/WS1 1998], [Whitcomb 2000], and [Yuh 2000].

Although terminology in this area is used relatively loosely, Unmanned Underwater Vehicles (UUVs) mean usually larger, torpedo-shaped vessels, which are targeted at autonomous long-range underwater cruising. Applications include oceanographical studies, geodetical surveys of the sea bottom, submarine and mine reconnaissance, etc. As examples of various UUVs, look at [Steer et al., 1993] and [Scott and Hewish 1999].

2.2.2 In-pipe robotic vessels

Another special application environment for mobile robots is the internal inspection of various pipeline networks. The scope includes inspection and maintenance of urban fresh- and waste water lines, as well as various gas and liquid pipelines in industry and power plants. Traditionally, more or less passive cleaning devices for pipelines have been called "pigs", but nowadays this term is also used for more sophisticated in-pipe inspection robots.

A tight, tube-like operation environment usually requires wheeled or multi-legged walking locomotion, and a flexible body to advance into corners and junctions. Most in-pipe vessels carry cameras, but ultrasonic or laser scanners are also widely used for corrosion detection. For examples of various approaches, see [Fujiwara et al., 1993], [Roβmann and Pfeiffer 1996], [Kawaguchi et al., 1997], and [Moraleda et al., 1999].

Despite demand, relatively few robots are designed for submerged on-line operation in flow conditions inside pipelines. As the latest innovation in pigging technology to respond to on-line requirements, *contra-flow traction* has been investigated. As is known, turbines have the ability to pull an object against a fluid flow. Based on this, promising demonstrations in autonomous contra-flow traction have been reported [Cresswell 1999]. This would allow a revolutionary passive travelling with and against the flow in the pipelines.

2.2.3 Towards reactive control and minimalism

In the early phase of AMR evolution in the 1980s, in many mobile robot projects a great deal of attention was given to the mere mechatronical development of a complex mobile robotic platform, rather than addressing autonomous control mechanisms or the practical application itself. Another key issue was the modeling of the unstructured operation environment. Typically, the control architectures of the early AMRs were complex and strongly hierarchical, derived from traditional model-based AI research. The weak point was the lack of adaptability: unexpected, non-modeled events could easily cause erroneous actions or even jam the whole robot.

To cope with the dynamic, ever changing environment encountered by mobile robots in real world, a revolutionary paradigm for the *behavior-based decomposition of an autonomous robot,* i.e., *subsumption architecture,* was introduced as a light alternative for increasingly more complex hierarchical architectures [Brooks 1986]. The idea was to decompose the traditional hierarchical, sequential, and planning-based (Sense-Plan-Act) model of the robot's task achieving behaviors into reactive, parallel running, but prioritized control layers. The resulting subsumption architecture responds fast to sensor information, and it leads to, or enables, either way, relatively simple control structures and hardware. These simplified ideas led to the boom of a new generation of experimental robots. Typical representatives of these kind of robots could be called *behavior-based robots* or *minimalist mobile robots*.

A great deal of literature concerning these matters has been written. Mechatronics design hints and practical hardware solutions for educational small-scale behavior-based robots can be found from [McComb 1989]. Minimalist and modular robotic structure supported by reactive control architecture is discussed in [Connell 1990]. It has to be noted that minimalism does not necessarily refer to small physical size, although minimalist ideas are in many cases easier to put into practice as small-sized. Another great mechatronics source book for a practical subsumption-approach for reactive robots is [Jones and Flynn 1993]. In this book, a detailed analysis of computational hardware, sensors, mechanics, motors, the power system, and programming are surveyed with practical suggestions for implementation. In [Steels and Brooks 1995], background issues for the design and implementation of autonomous robotic agents are widely discussed.

However, it is evident that complex tasks also need some high-level planning, meaning that very few real-world tasks can be successfully handled with pure reactive control. Therefore, it seems that *hybrid (deliberative/reactive) control architectures* provide the most feasible and reliable solutions for practical applications. The transition of paradigms in mobile robot control architectures is reviewed comprehensively in [Arkin 1998] and [Vainio 1999].

2.3 Cooperative multi-robot systems

By the end of the 1980s, robotics researchers became aware of the potential and possibilities in multi-robot systems. The challenging idea in these systems is not just to put a few robots to work in parallel in the same domain, but to achieve coordinated cooperation among the robots. Thus, in addition to lower level features presupposed in autonomous robotic operation, some *self-organization mechanisms* and *communication capabilities* are required from the robots cooperating in a group. Many terms are used in this context: *robot colony*, *robot society*, *distributed autonomous robotic system*, *cellular robotics*, *collective robotics,* or *team of robots.* Although the goal for these systems is ultimately the same, the definitions and emphasis on different features vary.

For example, Distributed Autonomous Robotic Systems (DARS) are defined in a general manner [Asama 1994]: "*DARS are the systems which consist of multiple autonomous robotic agents into which required function is distributed. In order to achieve given missions, the agents work cooperatively to operate and/or process tasks.*" The concept of Robot Society, discussed in detail in Chapter 3., also fits well to DARS classification. In any case, essential research issues for this field are distributed, but collectively coordinated sensing, planning, and control, as well as self-organization, communication, and user interface.

A coherent view to the development of ideas and multi-robot systems realizations can be obtained from the series of DARS -conferences, see [DARS 1992], [DARS 1994], [DARS 1996], [DARS 1998], and [DARS 2000]. For practical reasons, most of the multi-robot experiments have been carried out with wheeled and relatively small-scale mobile robots, which are inexpensive to clone. Perhaps the most well-known example of these small miniature robots is Khepera, for a detailed description, see [Mondada et al., 1994]. The operation environment for this type of robots has usually been a maze or arena set in a laboratory. Because of the relatively similar mechanical and electrical design solutions in the robots used for multi-robot experiments, the systems are best characterized according to their control architectures. In most cases, a hybrid architecture has been implemented to combine the best properties from both reactive and deliberative systems. See, for example, [Cao et al., 1997] and [Vainio 1999] for a profound study of the proposed multi-robot control architectures.

Distributed autonomous robotic systems is a relatively fresh area in engineering science, although it is gaining increasing worldwide research interest. Therefore, the theoretical foundation is still relatively undeveloped. Research work has been very experimental by nature with diverse approaches. There are no standard procedures on how to deal with multiplicity and cooperation in a group of robots. How does it affect the hardware structure of the robots? Should the hardware support the docking of robot bodies together? How should mutual communication be arranged? The lack of established tradition in the design of multi-robot systems complicates the design and implementation of such systems. On the other hand, in many cases, it has forced the introduction of new innovative solutions which might not have been discovered in other circumstances.

Furthermore, there exists no established formalism or method to systematically describe the functioning and interaction of robots. Comparing the performance of different control architectures is very difficult. In order to classify various DARS approaches, [Asama 1994] suggests some viewpoints:

1. *Top-down vs. Bottom-up approach*
   In the top-down approach, required tasks are divided and distributed into multiple agents. In contrast, in the bottom-up approach, the available agents are collected and organized.

2. *Analytic vs. Synthetic approach*
   In the analytic approach, it is investigated what can be achieved if each agent is equipped with certain mechanisms. Conversely, in the synthetic approach, in order to achieve the requirements, it is investigated what kind of functions are required for each agent.

3. *Homogenous vs. Heterogeneous systems*
   In homogeneous systems, every agent has the same attributes and performance as the others. This is often the case in DARS studies. In contrast, each agent can have individual characteristics in a heterogeneous system.

4. *With vs. Without communication*
   If communication is assumed, it means the intentional exchange of information. Without communication, each agent should be provided with a mechanism to infer cooperative behavior based on the information sensed. In some contexts, the latter means is called *indirect communication*.

5. *With vs. Without centralized agent*
   Decentralized systems have no centralized agent, while in centralized systems the central agent can be either predetermined or determined according to the situation. The centralized agent can be called master, leader, or coordinator.

6. *High vs. Low information processing ability*
   The level of the information processing ability depends on the assumption. For example, a low information processing ability in each agent is assumed for low level coordinated features, such as swarm intelligence, while high intelligence is assumed for dynamically reconfigurable robot systems.

7. *Tight vs. Loose relation*
   Generally, if agents become more autonomous, the relations between agents may loosen. However, in tasks needing frequent communication or synchronization between the agents, a tight dependence on the agents must be assumed.

2.3.1 Interactions and communication

Interactions in cooperative multi-robot systems are mainly achieved by local inter-robot communication. In some cases, indirect communication through environment sensing can allow coordinated behavior without explicit communication between the robot members. Because of its importance, communication issues concerning multi-robot systems have been widely studied.

To mention a few examples of noteworthy studies on multi-robot communication, in [Fukuda and Ueyama 1994], communication protocols, estimation formulas for the amount of communication in the system, formal representation for the sensitivity of the total system, etc., have been presented for a complex Cellular Robotic System (CEBOT) in general form. In [Balch and Arkin 1994], various generic multi-agent tasks were evaluated with different communication modes as a comprehensive simulator study. The results can be used to determine appropriate parameter settings for communication in a reactive control system. As an alternative way to promote local communication in a multi-robot system, an Intelligent Data Carrier (IDC) system based on tag-memories and read/write – devices has been suggested, see [von Numers et al., 1995] and [Kurabayashi and Asama 2000].

Nevertheless, as with most subjects in a multi-robot domain, because of the diversity of choice, truly general guidelines are difficult to find. Proposed solutions operate well in their original environment, but always require tuning and adaptation to new conditions. Good examples of such parameters are the *communication range*, i.e., the longest distance at which robots can receive messages from each other, and the *acceptable delay* related to the information of the messages.

2.3.2 Simulated multi-robot behavior

Due to the mechanical complexity and extensive mundane work needed in experimental set-ups for systematic research in a multi-robot field, a large number of simulation studies are reported. Simulations provide a useful tool to develop and test ideas, but it is vital that the simulator results can be verified with real robots as well. Unfortunately, many sophisticated computational ideas have not found their way into the real embodied robots. Perhaps the best insight into the computational developments in a simulator domain can be obtained from the Simulation of Adaptive Behavior -conference series, see [SAB 1990], [SAB 1992], [SAB 1994], and [SAB 1996]. A wide range of valuable background matters valid in DARS are analyzed in these issues. Ethology, biology, psychology, artificial life, machine learning, and constraints set by robotics form the mechanisms that allow artificial animals (*animats*) to adapt and survive in a dynamic environment.

2.4 Intelligent and mobile instrumentation

The current technological megatrend drives towards smaller, lighter, decentralized, application-tailored, more intelligent and independent, but wirelessly networked products and devices. This trend applies to instrumentation apparatuses as well, including sensors, measurement devices, data acquisition systems, and actuators. However, the sufficiently long-lasting energy supply remains consistently the biggest limitation to most stand-alone devices. *Passive mobility, miniaturized size,* and *wireless data transfer* provide opportunities for energy saving. As examples of recent development in the field of intelligent instrumentation, some novel passively mobile sensor systems are considered:

Case 1. Mobile dataloggers are used to record and file sensory inputs, which can be extracted from the logger's memory and analyzed off-line. Sometimes, dataloggers are called "micro-sniffers" or just "sniffers". Small-sized loggers can be attached or hidden in shipments or vehicles to validate transportation. Typical quantities measured are temperature, humidity, or selective detection of certain gases. The operation time can extend from months up to few years, depending on the sensors and sampling rate. For example, [Järvelä et al., 1998] reports a novel product where micromachined three-axis accelerometers are used to detect careless handling of goods during transportation. Recorded shocks, vibrations, temperature, and time can be analyzed afterwards.

Case 2. The dropsonde system for weather forecasting and hurricane research is an example of a disposable short life-time mobile sensor. Dropsondes are ejected from a high-flying aircraft. During the dropsonde's descent to the ocean, air pressure, temperature, and relative humidity are measured on-line. Precision GPS is used for tracking the exact location and trajectory, which also allows the calculation of wind conditions. All data are radioed back to the airplane and then sent further to a weather forecasting computer model via satellite connection. See [Vaisala 1999] for further details.

Case 3. There has been a lot of discussion on wearable or body integrated sensors and computers for healthcare automation and telemedicine. To assist in individual health care, [Yang and Rhee 2000] proposes a monitoring system in a finger wearable ring configuration. The sensor ring is equipped with optoelectric components that allow the continuous long-term monitoring of the patient's arterial blood volume waveforms and blood oxygen saturation non-invasively. These signals are transmitted to a home computer for further analysis of the patient's cardiovascular condition.

Case 4. Another medical examination instrument is a wireless capsule for measuring gastrointestinal physiological parameters. In [Iddan et al. 2000], a new type of video-telemetry capsule endoscope has been introduced. The capsule is small enough to be swallowed (11x30 mm) and has no external wires. It is propelled by peristalsis through the gastrointestinal tract without need for additional propulsion. The video images are transmitted using UHF-band radio-telemetry to antennas taped onto the body allowing image capture; video transmission is stored on a portable recorder. Lighting comes from an onboard white-light LED. The strength of the video signal is used to calculate the position of the capsule in the body. High-quality video transmission from the capsule can be maintained altogether up to six hours. The patient need not be confined to a hospital environment during the examination; no discomfort was reported from the first tests of the system on human volunteers.

Chapter 3

Applying the concept of the Robot Society

3.1 The Robot Society as an engineering concept

Robot society is a generic technical concept to control and describe a group of autonomous mobile robots operating together towards a common goal. The concept of the Robot Society (RS) has been introduced originally in [Halme et al., 1993]. Adapted from this paper, RS was loosely defined as follows:

"The Robot Society is a group of individuals, called members, with information and control structures. All members of a society need not be similar. Members having the same properties can form clusters or classes. The control structure defines how information is spread within the members, and how an individual member communicates with the other members of the society. The control structure defines the way the society affects its members. Because all working power is produced by the members, the control structure takes care of the task execution of the society."

...and the definition was continued by some practical considerations:

"The ultimate practical goal of the Robot Society concept is to construct a kind of "distributed robot", which can execute tasks which are defined by the user or "society controller", like in the case of a conventional individual robot. This means that the behavior of the society must be controllable outside, and the society must have an information connection to the controller. ... Basically, communication in a society is performed on member-to-member bases."

Since this early conceptual definition, the experimental development process of SUBMAR robots has given an explicit and practically verified content to the Robot Society control architecture and communication structure. Progress and the evolving of ideas during the architecture development has been reported, for example, in [Halme et al., 1996], [Vainio et al., 1997] and [Vainio et al., 1998b]. Despite the unconventional robotic embodiment and underwater target environment, the developed RS architecture is kept generic by nature, and can be applied to various purposes and environments. In [Vainio et al., 2000b] and [Vainio et al., 2000c] an overview of the main elements of RS architecture and a system level description of the application are presented.

The hierarchical three-layer RS control architecture consists of both reactive and deliberative components. Mutual communication is a key factor for the operation of the society. It can be divided into two categories: *communication between the operator and robots*, and *communication among the robots* (inter-robot communication). In Section 4.4 the model of the architecture and its practical implementation are presented.

Several control architectures suitable for controlling a distributed multi-robot system have been introduced, as reviewed extensively in [Vainio 1999]. From the control architectures found, ALLIANCE [Parker 1994] seemed to have the most similarities with the Robot Society. From the engineering point of view, a *minimalist approach* is especially supported by the RS. It means that the emphasis has been in developing maximally simplified, but still effective, easy-to-implement mechanisms for each robot to create *autonomously organized functioning* and dynamic interactions between the robots for the *cooperative behavior* to complete the desired tasks. If intelligence is assumed to derive from combining information, then, *intelligent behavior* can be expected from the system. Achieved high-level features, like dynamic reconfiguration of the society, belong to this category.

The performance of the society can be evaluated in many ways, for example, by considering *qualitative mission achievement, the duration of the mission,* or *survival of the robots*. Several parameters affect these characters. By altering the weight of these parameters, the operator has the ability to tune the society into a preferred operation mode. For instance, in some missions the accomplishment of the task is of the utmost importance, meaning that the loss of some robots is tolerable.

3.1.1 Advantage of multiplicity

Multi-robot systems in general, as well as Robot Societies, support parallel execution by nature. Therefore, they can be easily applied to such tasks as distributed perception, collection or the spreading of some physical material, sorting or separation etc. At a practical level, for example, the collection of nodules from sea beds, locating and cleaning toxic material in a hazardous environment, or planetary missions are suggested.

The technical advantages of a homogeneous Robot Society are clear:

1. The level of redundancy is very high in a society having a large number of similar members, which yields *fault tolerance* on a system level. It does not matter if some of the members break down, as the rest will be able to complete the original mission, although delayed.

2. The volume of the society, i.e. its operational efficiency, can be adjusted simply by increasing or decreasing the number of robot members. *Flexibility* is easy to

achieve in an open and completely decentralized system, which does not need any reconfiguration on a systems level.

3. Collective use of several robots enables relatively simple structures for a single robot member in many cases. Complex structures to ensure optimal functioning in all circumstances can be replaced by statistical assurance in a large society. *Simplicity* produces cost-effective solutions prepared for mass production.

4. In an optimal setup, once the structure for inter-robot communication is well tuned for the given task, the *effect of collective functioning* can be greater than the effect produced by the same number of members operating just in parallel. Literally, 1+1 may equal more than 2.

An increase in the number of robot members in the society improves the performance, but only up to a certain limit. If the optimal size of the society for a given task in a given environment is exceeded, the overall performance will begin to decline. This is due to the competition for space or other resources, like a physical "traffic jam" of the robots in a tight space or communication system overloading situation.

3.1.2 Collective consciousness

Consciousness is generally understood as a fusion of the individual's experiences at a certain time, including sensations, thoughts, imaginations, memories, etc. In non-human contexts, the term *animal consciousness* is used by cognitive ethologists [Allen and Bekoff 1997] to mean the ability of organisms to perceive (and in this sense be conscious or aware of) selected features of their environments.

As applied in the robotics world, without going into traditional AI subjects in a deeper sense, the term *robot consciousness* seems justified to mean the conception or assumption of a single robot from the state of its operation environment and task execution, as well as the robot's internal state and mode. *Robot awareness*, used for example in [Parker 1994], is a synonym for robot consciousness. With a Robot Society, robot consciousness evolves based on the possible a priori information it is given, the robot's own measurements, and information gained through communication. Consciousness is always a subjective experience, but in the case of robots, an external system observer can find it right or wrong. Summarized estimation of the robots' conception could respectively be called the *collective consciousness* of the Robot Society. Thus, monitoring the development of collective consciousness allows the system operator to obtain a general insight into the distributed robots' achievements. If information from other sources than the robots is also available, then the performance of the society can be easily evaluated. This type of testing has been documented in Section 5.4.

The fusion and combination of information from the robot's own sensors and from the distributed society through mutual communication is an essential issue in forming valid consciousness for the robot. Coherent collective consciousness is important for the robots' effective and coordinated operation. Basically, the validity and dynamics of robot consciousness derive from several factors:

1. Primary accuracy, resolution, repeatability, dynamics, etc., of the sensors used for perception
2. Sampling frequency (i.e., Shannon's theorem, [Shannon 1948])

3. Statistical and spatial reliability of the sampling
4. Throughput and coverage of the inter-robot communication network
5. Processing and fusion of measurement information from various sources in function of time (e.g., handling delayed information)
6. Number of robot members
7. Possible a priori information

3.2 Minimalist underwater robots as a case study

In the process industry the question of monitoring the internal state of the process in real-time, and performing local adjustments to reaction conditions are major problems. Normally the sensors used in monitoring are fixed and provide information only from certain parts of the process. Local adjustments are often difficult to implement, if not totally impossible. Overall control of the system does not allow local fine-tuning, which could offer considerable savings in materials and improvements in production quality.

In order to help the process operator with this problem, by allowing the sensors and actuators mobility inside a process environment, a robotized submerged platform to carry instrumentation was invented and developed. Certain features have been adapted and combined in a unique way from various types of systems: autonomous underwater robots, in-pipe robotic vessels, conventional wheeled multi-robot installations, and novel mobile instruments. As a result of this synthesis, the design of SUBMAR robots has evolved. The idea was to follow the minimalist approach, where the structure of the robot is maximally simplified. As a solution to compensate the obvious limitations derived from minimalism, multiplicity and cooperation of the robots were desired. Robot Society architecture was implemented into SUBMAR robots to verify its functioning.

The SUBMAR society consists of small-sized ball-shaped robots, which have a diameter of approximately 11 cm (see Figure 3.1). The robots are equipped with a micro-controller CPU, several sensors, tank actuators, and a short range radio for communication. Energy is carried in a battery pack. The mechatronics structure of SUBMAR robots is presented in detail in Chapter 4.

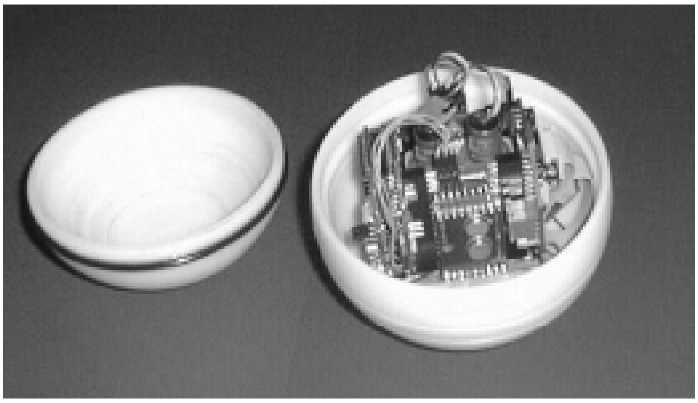


Figure 3.1 *SUBMAR, minimalist underwater mobile robot.*

SUBMAR robots feature a so-called *semi-active motion system*, i.e. they are capable to active vertical motion only by controlling their specific weight, otherwise, they move passively along a liquid flow. Due to the fact that motion energy is taken mainly from the process flow, the consumption of energy remains small resulting in long operation times, in practice several hours. Naturally, this kind of relatively stochastic motion system doesn't ensure access everywhere within the process, but in many cases it allows the robot to pass through the different parts of the process. Highly underactuated robots are prone to collisions, turbulence, and non-homogeneous flow profiles, benefitting that the trajectories for several robots are never uniform.

As is the case in many (multi-)robot related research issues, inspiration comes partly from nature. During millions of years of biological evolution animal species have gained astonishingly robust mechanisms and structures for locomotion, sensing, communication, interaction, and cooperation (see for example [McFarland and Bösser 1993]). Also, the Robot Society concept is influenced by features found from simple social animals, like ants and bees. Rather simple-looking features and local interactions that produce highly complex and effective global behaviors in insect colonies have been especially desired.

If biomimetic thinking is extended to the physical appearance of the robots, considering the Robot Society concept in context with SUBMAR robots, thinking can lead to the world of bacteria. Research in the field of microbiology has shown that even though an individual bacterium is a free-living autonomous organism, they can form complex communities, communicate with one another, and hunt prey in clustered groups [Shapiro 1988], [Shapiro 1995]. The analogy to bacteria is obvious, thus SUBMAR society can also be called *bacterium robot society* (see Figure 3.2). Bacteria are more than just simple unicellular microbial mass. These functional features are also sought after for SUBMAR robots, although their physical size is thousands of times bigger.

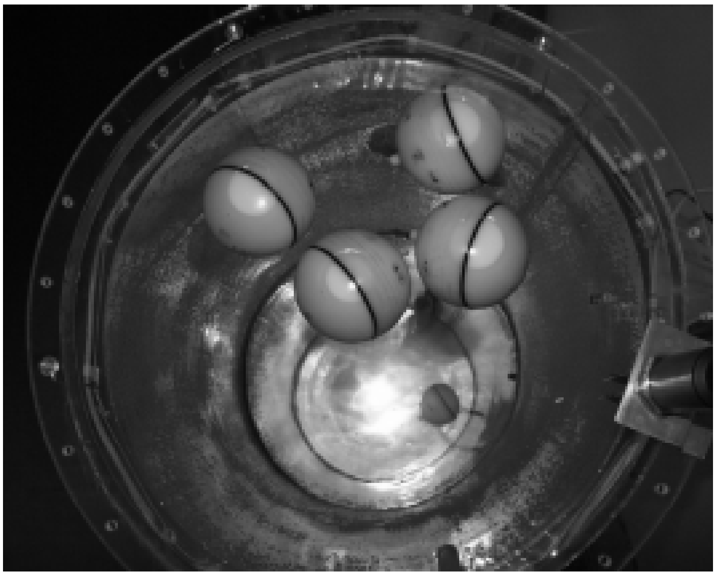


Figure 3.2 *An agglomerate of four robots in the surface of the tank executing a coordinated task; one individual (seen in the bottom) has left the group.*

The functioning of the system has been verified and analyzed with extensive testing, as presented in Chapter 5. To summarize the Robot Society approach as realized within SUBMAR robots, according to the seven attributes listed in Section 2.3, the system can be characterized as:

1. Having a *top-down approach*, since organization of robots is dynamic and the robots are capable of parallel multi-tasking.
2. The approach is *analytic*, as how a society having certain features can cope with a predefined task, rather than optimizing the features for that particular task, has been analyzed.
3. SUBMAR Society is *homogeneous*, where all robots are alike.
4. All the members are equipped with equal *direct communication* properties.
5. The functioning is completely *decentralized.*
6. Due to structures that allow dynamic reconfiguration and self-optimization, the society's behavior can be classified as *highly intelligent.*
7. The relations between members are event-based, not frequent, therefore the society can be assumed to have *loose relations*.

Chapter 4

Mechatronics structure of SUBMAR robots

4.1 Introduction

SUBMAR robots have been designed and developed as minimalist autonomous underwater robots for Robot Society studies in a laboratory environment. However, the structure of the robots has not been optimized for any particular environment, but the goal has rather been to verify the potential and limitations of a Robot Society system achieved by following the minimalist approach in robotic members. The mechatronics development process of SUBMAR robots took place in three prototype stages, called *Proto I, Proto II*, and *Proto III*, respectively. The latest, third generation design is presented in detail in this chapter. Note that throughout this thesis, the term "SUBMAR robot" refers to Proto III design, unless otherwise mentioned. Before going into the detailed analysis, the main features of the preceding generations are briefly introduced here.

The first SUBMAR, Proto I, was designed to test basic functions and features needed in this type of robot. Inmos Transputer module T222 was used as a CPU to enable rapid prototyping based on the known components derived from a previous robotic project. However, it was known already at the start that this processor would only be a temporary solution for preliminary studies. Design principles of the first SUBMAR prototype and some early ideas for the next generation were documented in [Appelqvist 1996]. The physical outer dimensions of the robots, i.e. the diameter of 10.8 cm, has remained the same in all prototype generations.

The main goal for the second generation, SUBMAR Proto II, was to put up the appropriate microcontroller hardware and develop basic software. Two copies of Proto II were constructed. The feature based environment mapping and positioning system was developed with these robots. Various sensors and communication methods were tested, see Chapter 6 and [Vainio et al., 1996] for more detailed information on these attempts.

SUBMAR Proto III, the latest generation design, includes all the functional features needed in an autonomous robot operating as a member of a society. A small series of ten robots were produced to form a demonstration society and an experimental testbed for laboratory environment. Progress in Proto III mechatronics development has been reported in [Appelqvist et al., 1997] and [Appelqvist et al., 1998]. The whole SUBMAR society is pictured in Figure 4.1.

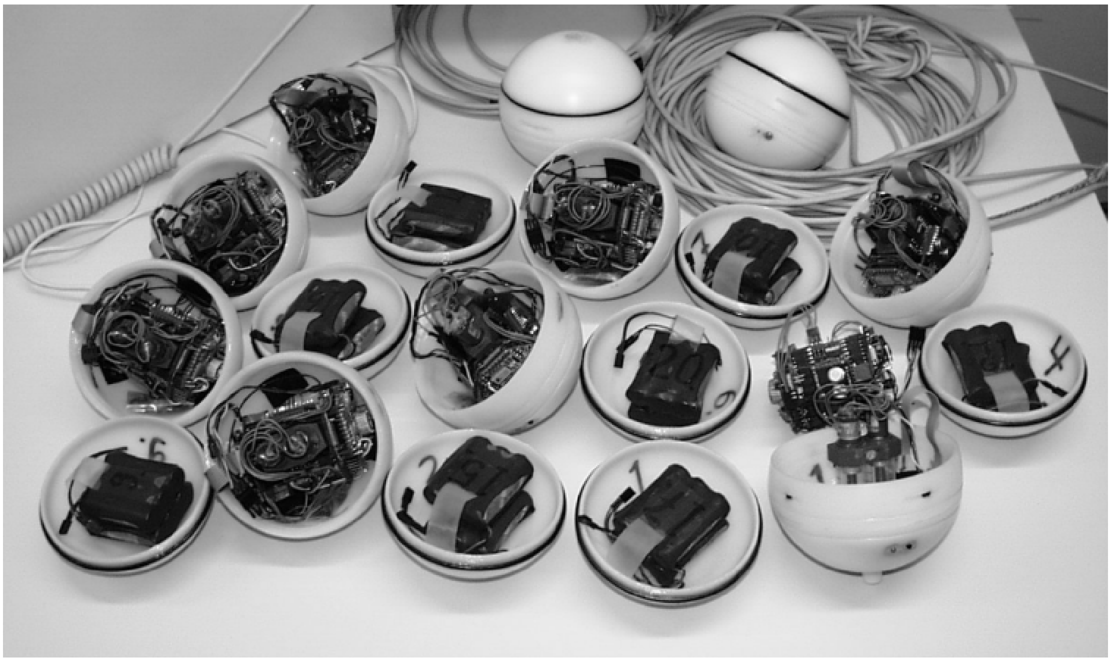


Figure 4.1 *The SUBMAR society in a family portrait.*

4.2 Mechanics

4.2.1 Casing

Ball-shaped casing forms a mechanically durable frame for a SUBMAR robot. The rounded form is practical, since the structure facilitates pressure resistance and does not get easily jammed in tubes, tanks, and so on. In addition to pressure resistance, the ball casing provides good shock and collision resistant characteristics as well. In industrial applications, other requirements would include extensive thermal and chemical resistance.

The casing is made of PA6 nylon. The outer diameter is 10.8 cm, having a wall-thickness of 0.6 cm. Parts are machined from bulk plastics, which makes it very expensive to manufacture; a larger series would require an injection moulding technique. The casing halves are closed with a thread of two and a half rounds, O-ring sealing, and sealant grease. Different sensors and actuators are attached through the casing wall and ensured with thread when possible. Lead-ins are glued and sealed from outside ensuring high pressure resistance. This construction has been tested up to at least 150 kPa in a pressure chamber as well as in practice during sea trials. Preliminary endurance testing also included boiling of the robot in a kettle; the robot survived operational and kept transmitting temperature data for hours with high temperature specified batteries in a temperature of 80 °C. However, in boiling water, the inner temperature rises, exceeding the limit and non-insulated batteries will lose their charge in a quarter of an hour.

Because of the internally located radio antenna, the casing had to be electromagnetically transparent. Otherwise, a metal cover or metal coating would be the easiest way to isolate the electronics from interference and electromagnetical noise. An antenna could be integrated into the casing, or installed as a flexible tail.

Although the ball-shaped form is clearly advantageous, effective utilization of the space inside can be problematic. The space, with an inner diameter of 9.6 cm, should be sufficient for all the electronics, sensors, actuators, batteries, etc. For a high-density integrated product where special solutions and components can be used the packing is not difficult, but for an experimental series of ten robots with a very limited budget the lack of space turns into a real challenge.

As a solution, the two tank-actuators are fixed to stand in the middle of the casing, so that the electronics unit can be positioned firmly around these tanks. Dual-row board-to-board interconnectors between the electronics modules have an important role in the construction, and no other supporting structures for the modules are needed. See Figure 4.2, where the schematic lay-out of a SUBMAR robot is illustrated in section.

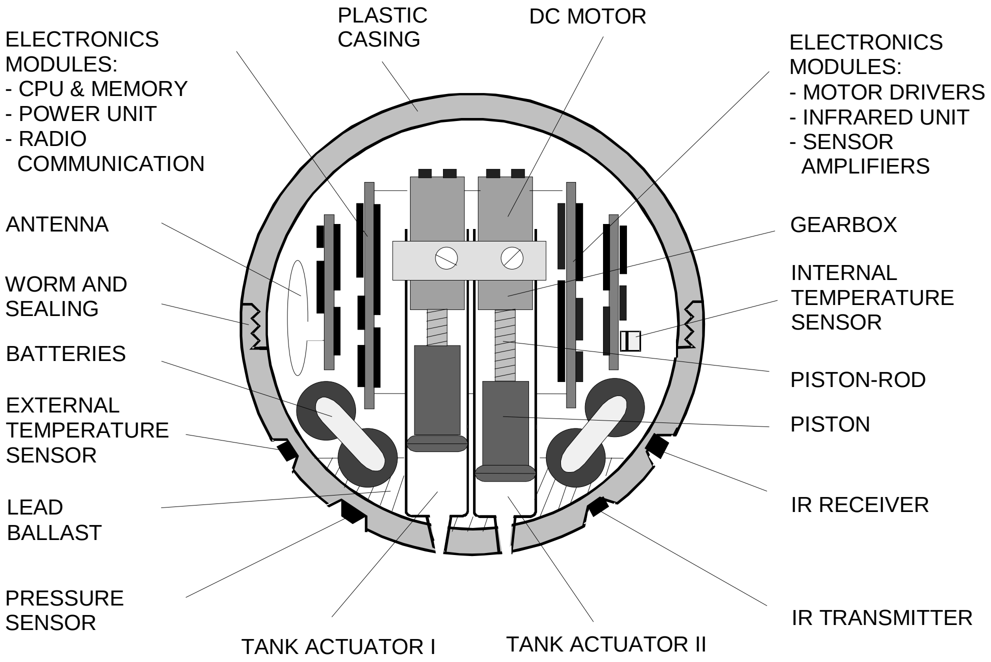


Figure 4.2 *Cross-section of a SUBMAR Proto III robot.*

Depending on the size of the battery packs used, they can be positioned in the robot in different ways, naturally affecting the robot's center of gravity and the weight needed in additional ballast. If the batteries are positioned below the electronics unit, then all the heavy components, including the pistons of the tank-actuators and additional ballast are placed as a keel to lower the center of gravity.

As a result, the robot's vertical orientation keeps relatively stabile, which is important for certain sensors. Unfortunately, with maximal battery capacity this was not possible to arrange. In Figure 4.3 a SUBMAR robot is shown with casing opened, and in Figure 4.4 the parts have been removed from the casing and disconnected.

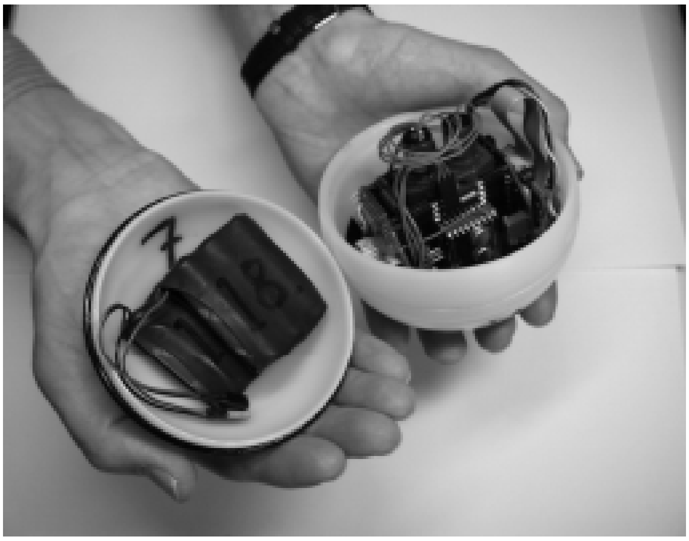


Figure 4.3 *SUBMAR Proto III cover opened.*

Figure 4.4 *SUBMAR electronics unit, casing, and battery packs.*

4.2.2 Tank-actuators

Because of the uncontrolled orientation of the robot body, traditional gripper-like actuators or most other types of mechanical actuators are useless. Instead, SUBMAR is equipped with two *multi-purpose tank-actuators*.

The tank-actuator consists of a driving motor, gearbox, screw-like piston-rod, sealed stainless steel piston, and a plastic chamber. The motor-gear combination used is a Maxon 0.5 W DC-motor united with a 200:1 reduction gearbox. This provides enough torque against high outer pressure with moderate power consumption. At a two meter depth, 0.13 W was measured for outward piston actuation. Sealing for the piston is adopted from an automotive brake cylinder. This type of V-profiled sealing-ring has very low slide friction against the chamber wall. The design of the tank-actuator has been illustrated in Figure 4.2; it is also shown in Figure 4.4.

This type of actuator can be basically used as a:

(1) *Diving tank,* to change the specific weight of the robot body by taking up surrounding liquid into the cylinder or vice versa. This allows the robot to perform vertical motion or balance its weight equal to the surrounding liquid.
(2) *Carrier tank,* to transport and spread a small dose of a chemical substance, for example, a reagent catalyst. The substance can be released at a certain location or once certain conditions are detected in the process.
(3) *Sample extractor,* to store a sample taken from the process from a certain location.

In the case of SUBMARs, the first two functions are verified. The diving tank function is used for moving and navigation, while the "carry and release" -task can be demonstrated with some colored marker substance, as in Figure 4.5. The chemical used was $KMnO_4$, which is not only a highly visual color in water, but in fact, also poisonous to algae. In practice, the two latter functions would probably require a controllable valve in the tank outlet.

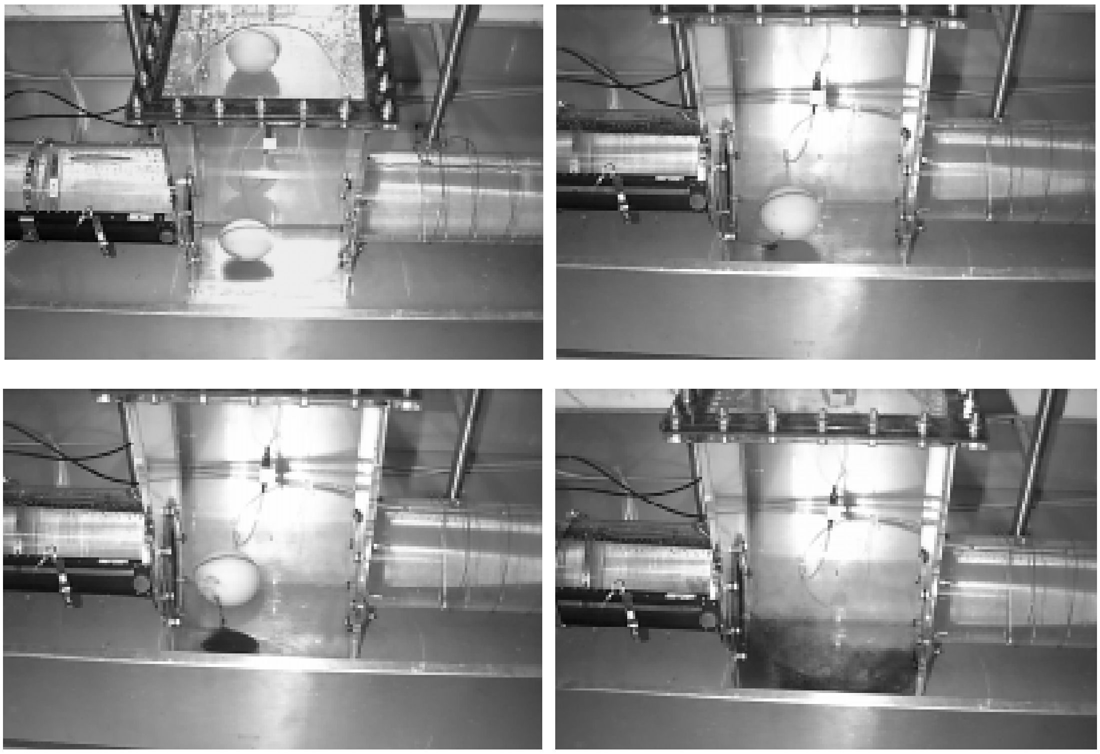


Figure 4.5 *A single Robot Society member demonstrating the carrier tank function. The upper left picture shows how the robot has detected the target area and lands on the bottom. In the next figure it starts to output a chemical substance. Below left, the robot spreads the substance at maximum speed, while in the last picture the robot has already left the tank and the chemical slowly disperses.*

Compared to the total volume of the robot body, which is approximately 650 ml, the volume of each tank-actuator, 4 ml, is very small. For this reason, the specific weight of the robot has to be initially set with an additional ballast relatively close to the surrounding liquid. On the other hand, when the tank is used as a sample extractor for an off-line analysis device, even 1 ml would be enough to serve a spectral analysator.

There are also other ways of adjusting the buoyancy than the presented tank-actuator construction. As an alternative means, a compressed gas system could be used to empty the ballast tank. However, this solution was abandoned due to the additional mechanical complexity.

4.3 Electronics

The main aims for the hardware design of SUBMARs have been a simple, compact, and modular structure. Furthermore, low power consumption, and reliable design in terms of EMC characteristics have been desired. SUBMAR hardware is founded upon an effective 16-bit microcontroller CPU, as shown in the electronics block diagram in Figure 4.6.

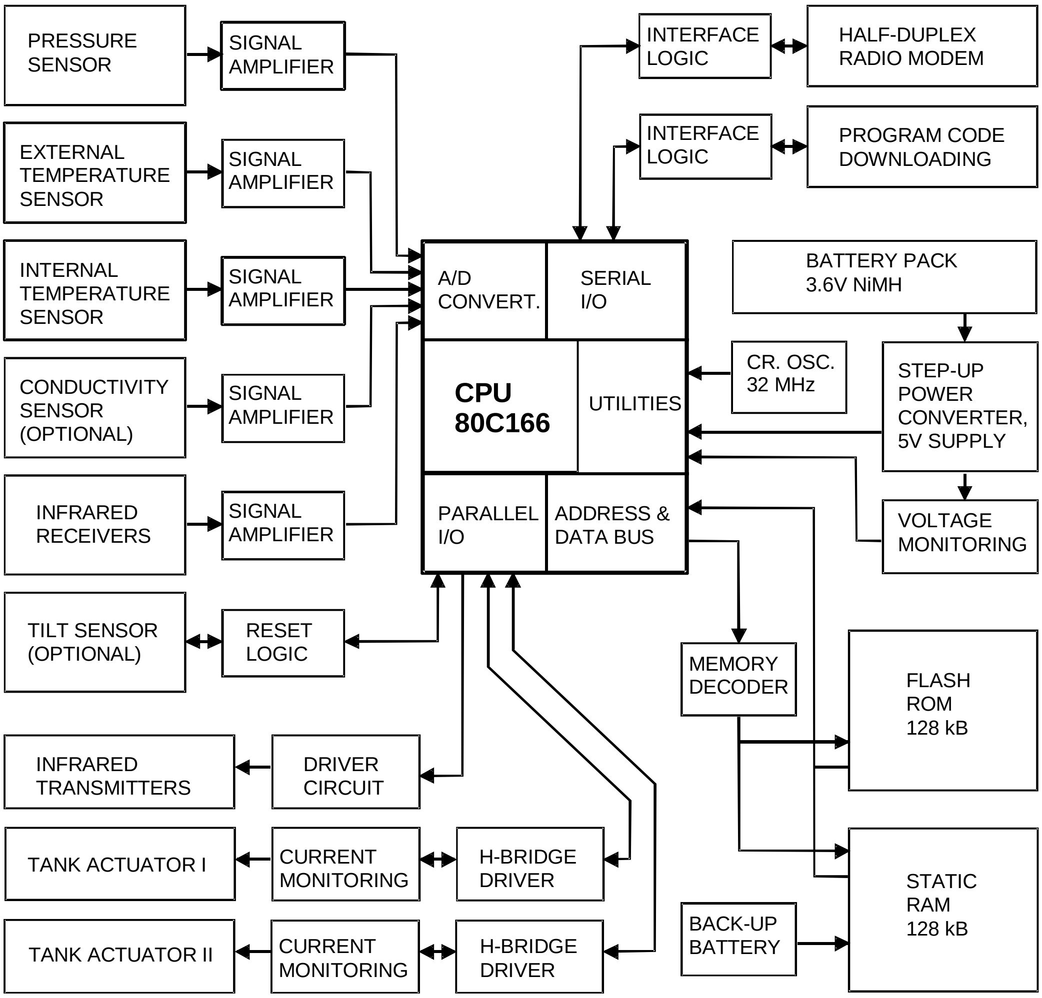


Figure 4.6 *Electronics block diagram.*

4.3.1 Hardware modules

Physically, the electronics unit is divided into six small separate modules:

(1) *CPU module*
(2) *Power module*
(3) *Amplifier module*
(4) *Motor control module*
(5) *Communication module*
(6) *Infrared module*

These modules are pictured disconnected in Figure 4.7. When connected together, these cards form a rigid structure which is inserted around the tank-actuators into the casing. Surface mounted components are installed on both sides of the circuit boards in each module to save space, except in the Infrared module, where traditionally mounted components are applied. In addition to these modules, the actual *sensor elements* attached to the casing (see Section 4.3.2) and two *battery packs* belong to the electrical hardware.

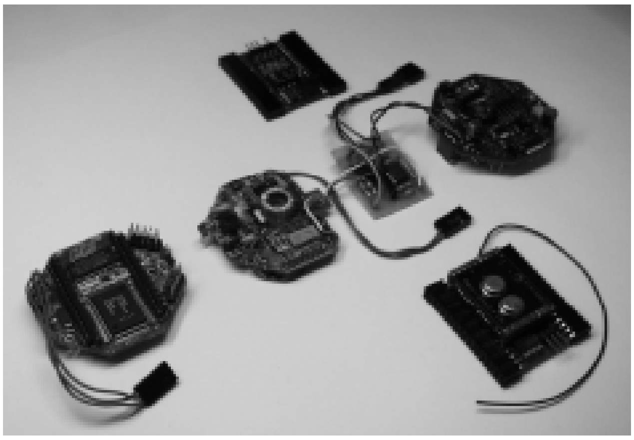


Figure 4.7 *Electronics modules disconnected.*

(1) CPU module consists mainly of the processor and memory circuits. The processor is a 16-bit Siemens 80C166 microcontroller. Instead of a maximal 40 MHz, this CPU is operated at a 32 MHz clock frequency as a compromise between power consumption and computational speed. However, even with slightly reduced speed, the CPU is still more than capable of handling its loading.

A total memory space of 256 kBytes supported by the CPU is available. Therefore, an 18-bit wide address bus is used, while a data bus is multiplexed to 8-bits wide. Most of the memory circuits are located in the CPU module; 128 Kb of Flash EEPROM for the program code, and 64 Kb of SRAM for the processor RAM and data storage. I/O-functions, A/D-converters, and serial communication channels are provided straight from the microcontroller, which enables compact design with few external components.

(2) Power module provides a 5 V supply voltage for all the components. The input voltage range (2.8…4.5 V) for this DC-DC step-up converter is configured for 3.6 V battery voltage. Therefore, a battery pack has three NiMH cells in series, since the nominal voltage for each cell is 1.2 V. The remaining unoccupied space in

the casing allows the fitting of two parallel sets of triple AAU-size *battery packs,* giving a total capacity of 2.7 Ah at 3.6 V. Operating with normal processor loading, basic sensors, actuators, and communication in modest use, the average power consumption for a SUBMAR is approximately 1.5 W, which allows up to 6-7 hours of operation. However, depending on the nature of the task and utilization of the actuators, the power consumption can be considerably higher.

Apart from the power supply unit, there is also an array of seven small indicator LEDs connected to the I/O of the microcontroller. They can be used to give various status signals on the robot's setup to the user, but they are also extremely valuable while developing and debugging embedded software. Furthermore, an additional 64 Kb of SRAM for data storage is fitted into this module.

(3) Amplifier module has the required analog circuits for signal amplification and conditioning for each sensor output. The absolute type of pressure sensor for depth sensing, internal and external temperature sensors, as well as a conductivity sensor are included. Excluding the internal temperature sensor, other actual sensor elements are naturally mounted as lead-ins in the SUBMAR casing.

(4) Motor driver module consists of small on/off –style MOSFET H-bridge drivers for each of the motors of the tank-actuators. They are monitored by current sensitive detector circuits, which can be used as simple limit switches for piston movement. The motor current, and therefore voltage loss over a very small series resistor, rises rapidly once either end of the cylinders is reached. This signal is used as an interrupt source for the CPU to halt motor driving quickly. This is an especially important feature if the motors are driven with feedback from pressure, i.e. in depth control, when large overshoots in the piston position are inevitable due to slow control dynamics. Otherwise, the tank-actuator pistons are driven only with respect to time.

In the motor driver module, there are also two DIP-switches, which can be used to select different software configurations, and an optional tilt sensor with reset logic for navigational purposes.

(5) Communication module utilizes Radiometrix's BIM-433-F half-duplex UHF radio transceiver with a simple λ/4 wire antenna. With this miniature RF modem, transmitting and receiving serial data in ASCII format is supported with a 9600 Baud. The transmit frequency is 433 MHz. Only one additional logic component is needed to connect the radio to the TTL-level serial port of the microcontroller.

Low transmission power of 10 mW is enough to guarantee communication distances over 120 meters in open space in the air, and typically 30 metres inside buildings. Surprisingly, even a radio frequency as high as 433 MHz proved to provide reliable, power effective, and easy-to-apply connections to both the operator interface and robot-to-robot communication in laboratory experiments in fresh water. Under these conditions, the maximum underwater communication range is limited approximately to 1.5 meters in optimal antenna polarization. This supports well the desired local communication abilities for SUBMAR Society studies. It is only appropriate that not all robots are accessible at once. However, for conductive liquids, like sea water, the communication range drops to zero. It goes without saying that the carrier frequency of the transmission is far too high to be useful in any real world application in submerged use.

(6) Infrared module belongs to the context of the emulated biomass growth system, explained in Section 5.1.2. In this module, there is just a simple FET driver for IR LEDs and a two-stage signal amplifier for IR phototransistors. A description of the IR components selected is in Section 4.3.3. Basically, by connecting this module to the serial port of the CPU, IR light could also be used for local communication in clear liquids. This type of dual-purpose IR based sensor/communication system for wheeled multi-robot experiments has been described in [Suzuki et al., 1995].

When connected together these modules form a compact and rigid structure, as illustrated in Figure 4.8. Once placed around the tank units in the casing, three connectors are used to attach the wiring from the casing mounted sensors to the electronics unit. A detailed schematic layout of the electronics of each module and sensor connections are presented in Appendices A-F.

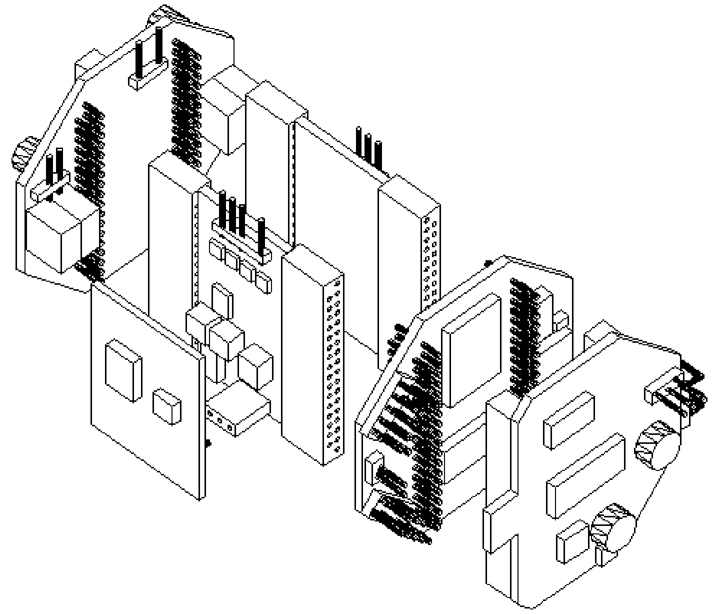


Figure 4.8 *Assembly of the electronics unit.*

4.3.2 Sensors

For depth monitoring, SUBMAR is equipped with Siemens KPY 42A silicon piezoresistive *absolute pressure sensor*. An absolute type of sensor has to be used, since the inside pressure of the casing varies depending on the position of tank-actuator pistons. The pressure range for this version is up to 60 kPa, which equals 6 meters depth in water. Large deviations in bridge resistance occurring in a series of this type of sensors make an accurate calibration process complicated, since the small-sized wide-range potentiometers needed for amplifier gain tuning are relatively inaccurate. As a result, in addition to the hardware calibration to get comparable absolute depth measurements, the pressure sensor is also software calibrated during an initial calibration dive before operation.

As an *external temperature* sensor, the Analog Device's AD 590KH is used. To correct the effect of heat generation from the electronics unit, another sensor is installed to monitor the *internal temperature* in the casing. The AD 590JH type is being used for this purpose.

There are very few small-sized conductivity sensors available on the market, thus, a suitable *conductivity sensor* for liquids was simply constructed from two isolated electrodes. To prevent gas generation and fast electrode corrosion, an AC signal has to be applied to the electrodes. Although the actual gold-plated electrodes were installed only into a single casing for testing purposes, the oscillator and amplifier circuits needed in conductivity measurements were included in each robot's electronics for possible future needs.

4.3.3 Emulated instrumentation

The *infrared light sources* installed into the robot's casing could be understood as actuators in this context. IR light is used to emulate chemical substance propagation from the robots in the emulated biomass growth system developed for the task execution experiments (see Section 5.1.2 for details).

For that purpose, there are three Siemens SFH487P -types of IR LEDs mounted to the robot casing. Once installed on a horizontal plane pointing in opposite directions, just three of these LEDs connected in series provide a sufficient transmission pattern covering a relatively wide radial sector. These LEDs have a half-angle of +/- 65 degrees, which, as a drawback, results in relatively low emitted IR intensity. The peak emission wavelength at 880 nm corresponds to the respective IR phototransistors found in the emulated biomass panels.

Infrared light detectors in the robots emulate a sensor for dissolved gas which originated from the artificial biomass growth. In the same omnidirectional configuration, next to the IR LEDs, there are three parallel Siemens SFH 309 PFA infrared phototransistors installed into the casing. These phototransistors feature a very wide half-angle of +/- 75 degrees and the same 880 nm peak wavelength for detection.

4.4 Software

All the features needed for autonomous and cooperative functioning, as well as available *a priori* information related to task execution are included in the embedded software running in the robot's microcontroller CPU. General reliability and robustness against unexpected events in the environment are the most important aims and challenges in mobile robot software design.

The software for SUBMAR robots which enables basic functional features and execution of the tasks described in Section 5.2 consists of some 6600 lines of relatively loose-written C source code. Once compiled, assembled, linked, located, formatted to an Intel Hex -format, and downloaded into the robot's Flash memory, the program occupies about 105 kBytes. As a software development environment, the C166 Compiler Package V5.0r5 by BSO-Tasking and SFD V2.0 debugger by RTDS have been used.

The functioning of the robots is partly stochastic by nature due to the underactuated motion capabilities and relatively inaccurate areal positioning system. Therefore, there is no need for a very high speed control or sensor sampling. The program cycle containing sampling of the sensor inputs and updating the state of the whole control structure is executed only once per second. Depending on the length of the program path and required amount of computing at each time, it takes 70 - 80 ms for the CPU to update the state of the control structure with the given tasks. The faster frequent interrupt configured for 100 ms cycle time is used mainly for motor control. With this loading the chosen 16-bit processor is obviously unnecessarily powerful. A lot of computational resources remain unused for future needs and software experiments. On the other hand, more frequent communication and/or increase in the number of robots in the society can cause considerable additional loading for the CPU.

4.4.1 Control architecture

The control architecture defines and outlines not only the functioning of a single autonomous robot, but also the collective operation of the whole society. In the case of the Robot Society, the functioning is represented with a hierarchical, three-layer control architecture (see Figure 4.9). The *behavioral, task,* and *cooperative layers* of the RS architecture consist of reactive features for fast response to the signals from the dynamic environment at a low level, as well as deliberative, tactical and strategic models for operation at higher levels. Therefore, SUBMAR society can be said to have a so-called *hybrid architecture*. Development and earlier versions of the RS architecture are presented in [Vainio et al., 1998a], [Vainio et al., 1998b], and [Vainio et al., 2000a]. A profound presentation of the architecture, analyzed in a more generic form, can be found in [Vainio 1999].

In the following, the functions of the three control layers are discussed. From the point of software implementation, at first, the desired tasks need to be decomposed into subtasks, and their mutual relations have to be analyzed and structured. Then the model of the control architecture serves also as a tool to outline the desired functioning of the whole society, which should help in the practical program coding. In an embedded, interrupt based, pseudo-parallel program code the control structure itself is difficult to pinpoint. It has to be understood rather as a part of the program structure, than some specific part of the program. After all, the complex-looking multi-tasking behavior of the society is achieved by combining simple conditional rules whose priorities are well defined.

4.4.1.1 Behavioral layer

The behavioral layer manages the lowest level behaviors of the robot functioning as an interface between the robot and the environment. This is done by continuously monitoring the sensor inputs and internal resources, as well as the received communication from the other robots or the operator. Information and data from these various input sources is fed to a Finite State Automata (FSA), which determines the respective *state* for the robot. For the experiments presented in Chapter 5, five behavioral level states are implemented, but always only a single state is possible in one go. The active state defines the robot's low-level behaviors and functioning, i.e. how the actuators are used and what messages are transmitted out. Behavior level states are prioritized according to their importance in the robot's survival. Other criteria are also possible, such as the preference of mission accomplishment at the cost of lost robots.

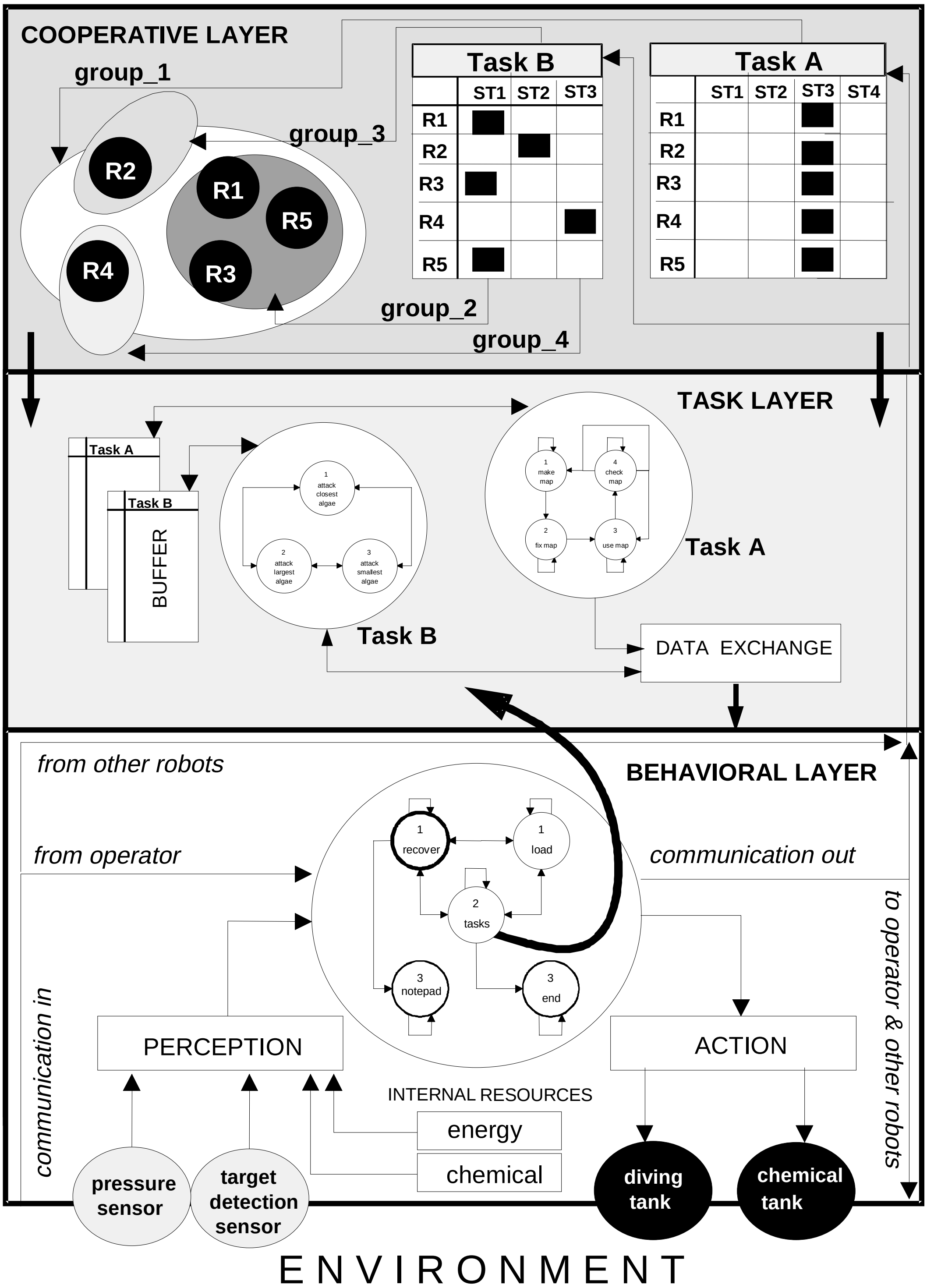


Figure 4.9 *Robot Society control architecture as applied to SUBMAR robots.*

Five behavioral level FSA states belong to current implementation: *recover, tasks, load, notepad,* and *end*. The states *load* and *recover* represent low level behaviors with the highest priority (self-sufficiency behaviors). The actual task achieving behavior is the *tasks* state. The *recover* state is the initial state for the robot, when power is turned on. It is also a kind of emergency state, active when the robot detects that something is wrong with its mobility (e.g. its location has not changed even though it should have). In this state the robot starts to use its tank-actuators extensively. The robot changes its status to *notepad*, if *recover* has failed to make it mobile again. In this state the robot no longer moves actively, and its only useful feature is to operate as a kind of message mediator until its energy runs out (abnormal termination). When the robot enters *load*, it detects that either the level of spread chemical or its energy have reached some threshold value, so it navigates to the recharging and refilling station. Consumption of these internal resources is modeled and realized as emulated functions, since the chemical substance carrier task is emulated itself and the real battery capacity allows longer operation time than required in a one-hour experiment run. In the *end* state, the robot has completed the mission, the mission time is finished or the operator has given the command to abort the mission (normal termination). Then the robot navigates to a defined location (home) waiting to be removed from the demo process.

4.4.1.2 Task layer

Since only one state in the behavioral layer is allowed for the robot at a time, the actual missions the robot is executing in the *tasks* state are defined in the next level, the task layer. In this layer, each task can be divided into subtasks and then presented as an independent FSA. These FSAs are executed in parallel enabling a true higher-level multi-tasking capability for the robot. From the point of software implementation, this means that various tasks are easy to isolate from each other, which supports the desired modularity for a program code level. The testing and debugging of software, as well as managing and the allocation of hardware resources becomes much easier.

If another state with a higher priority than *tasks* in the behavioral layer's FSA becomes active, for example, if the robot is running out of energy, the necessary information concerning the state of each task is stored in buffers. When the robot program allows the performance of the actual tasks again, the robot retrieves the needed information from the buffers. Also, data exchange between different tasks is needed, and it has to be ensured that there is only one output command for the actuators at a time.

One or more pre-programmed *strategies* exists to execute a certain task. Furthermore, if there are *measures to evaluate the efficiency of these strategies* according to some common criteria, then it is possible for the robot to optimize its own performance. In the explore and exploit –type of mission evaluated in the experiments described in Chapter 5, two parallel tasks were executed. One consists of the *feature-based positioning and navigation system* (Task A), while the other is *emulated biomass growth detection and removal* (Task B). These tasks are explained in Section 5.2.

4.4.1.3 Cooperative layer

The cooperative layer stores and utilizes the information gained from the other robots through inter-robot communication. This information can be either measurement data or some parameters related to the robots' task execution. Robots having the same strategy form a *group*. Individual robots can belong maximally to as many groups as there are different tasks, while the maximal amount of members in a group correspond to the total number of robots.

Cooperation enables optimization of the task execution at the society level. The robots commence by testing various strategies. After testing, the functioning continues with the best combination of strategies so far. Then, a robot's own efficiency values are compared to other robots' achievement figures received from inter-robot communication. In this way, successful robots having the right combination of strategies can recruit other robots to the same group. As a result unsuccessful robots change their strategies to better combinations. Stagnation to sub-optimal combinations in a dynamic system is unlikely if the threshold for transitions between the groups is made small enough. Instead, finding the optimal combination in a complex system containing many possible strategy combinations can take time.

Regardless of the type of data or its origin, the reliability of the data decreases over time. The faster the dynamics of the process, the sooner the data becomes unreliable. For this reason, the parameters monitored are stored into databases, i.e. to dynamic arrays, which contain rows for the parameters and columns for each robot. Each cell in this array includes fields for the *parameter value* itself and the respective *weight coefficient* for the reliability of the data. Once new data is received and stored into the database, an initial value is set as a weight coefficient. The value of the weight coefficient is decreased frequently, until it reaches zero. At that time, the data is also swapped away from the database. A weighted average calculated for each parameter from the available data from the robot's databases represents the collective consciousness of the society.

In the experiments, the weight coefficient was decremented once a second, while the initial value was 1000. This means that a certain data is available in the robot's memory for about 16 minutes. In this case, weight decrementation is linear, but to emphasize fresh values, an exponential forgetting factor could be used instead.

4.4.2 Communication structure

The organization of the communication structure is closely related to the control architecture. Low-level *communication protocol* is used to create a reliable point-to-point or broadcast type of transmissions in the short-range radio network. On a higher level, the appropriate *handling of the contents of the message* is arranged.

4.4.2.1 Low-level protocol for communication

As mentioned earlier in Chapter 3, communication in a robot society can be divided into two categories: *communication between the operator and robots*, and *communication among the robots* (inter-robot communication). The former enables the user interface to control the society, while the latter is needed to turn a group of robots into a cooperative society. Since all of the data exchange in the society is carried out under a common radiofrequency, some sort of communication protocol is essential. As a solution, an Ethernet (CSMA/CD) inspired distributed protocol adapted for wireless communication was developed and implemented to SUBMAR robots. A similar type of approach for a CSMA-based wireless communication system for cooperative robots has been reported in [Premvuti and Wang 1994] and [Wang and Premvuti 1994], as well as in [Hutin et al., 1998]. The aim has been to support efficient messaging with minimal loss of information. Messaging with the protocol only requires that each robot is given an unambiguous identification number (ID). The robot asks the operator for its ID number once the power is switched on. The protocol frame is presented in Figure 4.10.

Each message consists of two sections according to the protocol frame: message title and the actual information to be transmitted. The frame begins with the start byte *STX* (ASCII mark "S"), which is used to synchronize the connection between transmitter and receiver. It is followed by the protocol *Version* number, currently 1 (0x01). The *Sender ID* -field in the protocol frame is for the robot's own identification number. *Receiver ID* enables message addressing to a certain robot member, while broadcasting to the whole society is defined by setting the receiver as 255 (0xFF). The operator's ID is agreed to be 1, while a robot without a given ID is 0. In protocol version 1 the number of members is limited to 253 to save bytes in the frame, but in principle there is no limitation for that number.

Item	Bytes	Explanation
Message title :		
STX	1	Start byte
Version	1	Version number of the protocol
Receiver ID	1	Receiver's ID-number
Sender ID	1	Sender's own ID-number
Message type	1	CMD, INFO, ACK, NACK
Message ID	1	ID-number of each message from a certain sender
Data length	2	Length of payload
Title CRC	2	Title checksum, CRC polynomial in reverse order
Payload CRC	2	Payload checksum, CRC polynomial in reverse order
Payload :		
Data max.	65520	Actual message

Figure 4.10 *Message frame for the communication protocol.*

Four different *Message types* are supported: *INFO*, *CMD* (command), *ACK* (acknowledge), or *NACK* (no acknowledge). Info messages are intended for regular transmissions, like a robot sending its measurement data to the process control station. Important messages can be sent as a command type, which means that receiving of the message is ensured by the acknowledge request. For these acknowledgement purposes, each message sent by a certain robot also contains a *Message ID* number. If the message type is CMD, the receiver automatically generates and sends back an ACK or NACK type of message to the sender. In these cases, the payload is left blank.

Info types of messages provide no confirmation to the sender whether the message was received. However, for all message types CRC polynomial checksums are calculated to protect messages from transmission errors caused by noise or other interference. *Data length* reveals the length of the following payload, which is needed for the CRC algorithm; title length always remains constant. *Title CRC* and *Payload CRC* are calculated separately to speed up message handling. The protocol frame does not limit or determine the format of the actual payload message. The structure of *Data* is left completely open in the transmission layer of the protocol, except the maximum size, 64 kBytes.

Then there are some parameters which can be adjusted to tune communication to the existing environmental conditions. *Automatic resends* are used in context with the INFO type of message; the probability of correctly received messages increases radically, if each message is always resent one after another a few times. Also, the number of *Acknowledge retries* can be set, as well as *Acknowledge timeouts*, the time before the next retry. *Carrier signal detection* is used to prevent overlapping transmission; in very noisy environments it can be useful to switch it off. The *user interface* of the society is described in Section 5.1.3.

Before running the experiment series documented in Chapter 5 the inter-robot communication system in the SUBMAR society, as well as the user interface, was set to a desired "realistic" throughput level. Altogether, the aim was to achieve a local communication ability where not all the messages are received, rather than optimizing the communication setup for the test.

During the preliminary testing it was soon realized that the CMD-type of messages had a very poor success-rate with our radiofrequency media in an underwater environment, although the system worked reliably in the air. However, this did not affect the experiments concerning robots' mutual communication, since CMD messages were originally specified only for the user interface for abnormal interrupts. As a result, the user interface is realized with the INFO-type of message as well.

4.4.2.2 High-level handling of messages

Once a message is received correctly by a robot, as well as addressed to that particular robot, the contents of the message are identified with the first characters of the payload. *Messages from the operator* have highest priority and mainly affect the behavioral layer. In the case of an autonomously operating robot, regardless of the robot's active state, the operator must always have the access to interrupt the program execution and give manual controls instead. For example, the command "HO" gets the robot to navigate back to its home nest, or "UP" makes it come to the surface, while "BL" sets the robot back at its autonomous operation mode. The operator can also naturally request for some status information or data, which does not affect the robots' autonomous functioning.

Inter-robot messages are directed straight at the cooperative layer of the control architecture. These messages contain measurement data related to the active tasks, or success-rate values of the executed strategies. The collective consciousness and global optimization of the task execution in the society are based on these messages. As an example of an inter-robot message, "ASxxxxyyyy", is a message where the x-field contains the number of the chosen strategy and the y-field the success-rate value for that strategy. Regardless of the values, both fields are always expressed with four digits.

Chapter 5

Experiments with the SUBMAR society

5.1 Test environment

5.1.1 Demo process

Practical testing of prototypes and experiments with the SUBMAR society have been carried out in a special laboratory test environment, called here the "demo process". This fully transparent process environment is not a model of any existing industrial process, but consists of different types and shapes of typical process parts (see Figure 5.1). The total volume of 700 liters is filled with fresh water. In order to imitate process flow, water is circulated with a jet-flow pump. Other instrumentation includes several temperature sensors, pressure sensors, a limit switch for the liquid level, and an ultrasonic flow-speed meter. Magnetic valves control hot and cold water inputs, which can be used to generate plug flows and temperature gradients to be measured by the robots. The instrumentation is controlled from a PC-based automation system.

5.1.2 Emulated biomass system

To enable the study of the functioning of the distributed control architecture of the Robot Society, a dynamic multi-target mission for the robots was desired. In order to acquire statistical data for the analysis, the mission had to be exactly repeatable in each run. As a solution, a special *emulated biomass system* was developed for the demo process environment. This system can be used to emulate the growth process of a biomass, for example yeast, or algae, as in our case, which tends to occur in closed water systems.

The task for the robots is detection and removal of the unwanted algae growth agglomerates, which is achieved by distributing a poisonous chemical to the growth locations. This task deserves some comment from a practical standpoint. Instead of eliminating the unwanted microbial growth locations by raising the poison concentration to an adequate level throughout the process volume, the same task can be treated with coherent local actions by carrying the minimum amount of poison to areas where it is needed.

The behavior of the emulated growth spots, as well as the robots' sensors and chemical substance distribution facilities, are presented by infrared LED and phototransistors, as illustrated in Figure 5.2. For the experiments, the growth model for algae is parametrized in such a way that it is impossible for a single robot to remove all the growth alone; cooperation is needed. This allows the analysis and evaluation of the parallel multi-tasking of the robots in a spatially distributed task execution.

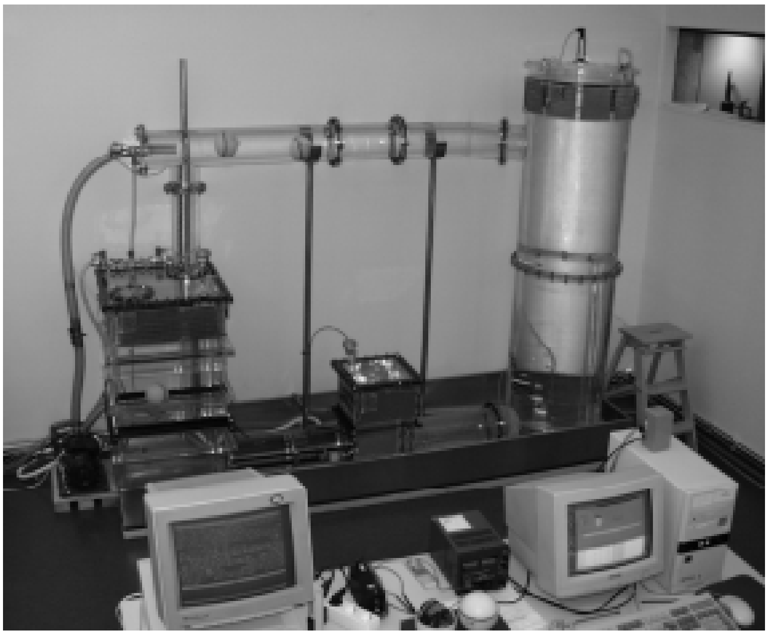


Figure 5.1 *The demo process test environment and user interface for the operator. Three robots are visible inside the process.*

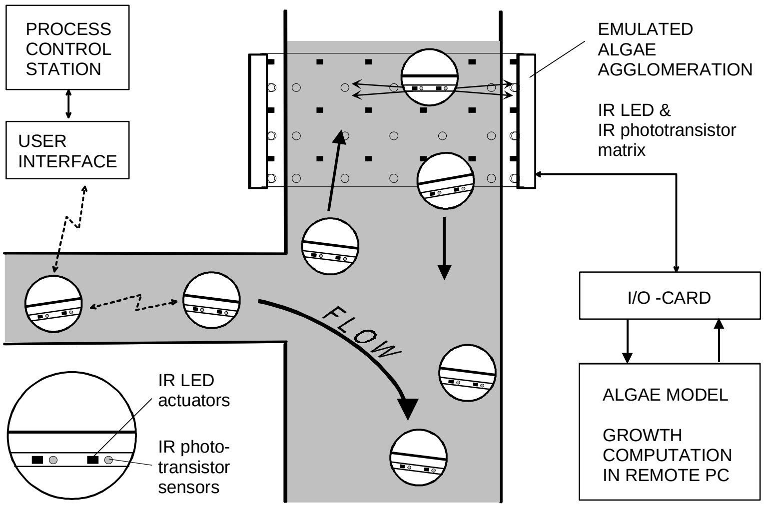


Figure 5.2 *An emulated biomass system describes algae growth in the demo process. The growth agglomerates occur in locations where water stands still.*

Light emitted from the IR LEDs of the emulated algae represent oxygen or some other gas produced by microbial growth, which in reality could be detected by robots with an appropriate dissolved gas sensor. Robots have IR phototransistors as dissolved gas sensors; while lighting their IR LEDs, robots emulate the spreading of the cleaning agent for algae removal. The emulated organism reacts to the presence of the poisonous chemical, i.e. IR lighting, through its IR phototransistors. There are three (only two were used in these tests) independent growth agglomerations installed at different locations in the demo process (see Figure 5.1 for their locations) on the upper section of each tank. The electronics driving and sampling the IR panels are controlled from a PC via an I/O-card. Transmission of IR light can be analog or frequency modulated. In the tests, more realistic analog modulation was used. The sensed signal level depends on the measuring distance, which is a familiar challenge in real-world applications, too.

Calculation of the current level of biomass and its growth rate at each spot is carried out in a remote PC. The behavior of the biomass is modeled with a generalized growth curve typical to most biological growth processes (see, for example, [Stanier et al., 1990]). The status of an algal growth, *A*, (i.e. volume of biomass) is based on a formula which indicates how the derivative of the algae is related to the growth and natural death of the cells, as follows:

$$\frac{dA}{dt} = (\mu - D) * A \qquad \text{(Eq. 5.1)}$$

where μ is the growth rate and *D* is the death rate of the organism. The value of μ depends on the limiting substrate (for example, nitrogen). The death rate becomes meaningful when the age of the cells increases or when some poisonous substrates (i.e. cleaning agent) are released into the environment. The actual equation used in our model is discretized from Equation 5.1:

$$A(t+1) = A(t) * e^{(\mu - D)\Delta t} \qquad \text{(Eq. 5.2)}$$

The value of *D* is related to the concentration of the cleaning agent. This value can be detected through the output channels from the growth agglomerate. The generalized growth curve of a bacterial culture consists of four separate phases: lag phase, exponential phase, stationary phase and death phase. These phases are shown in Figure 5.3, where the biomass value A, produced by the model, is plotted. During the exponential phase, there is an attack made by a single robot. As a result, the value of the biomass drops for a while, but it continues to grow immediately after the poison is dissolved.

Each growth area consists of four IR phototransistor/LED panel sections. The maximum concentration of cleaning agent sensed by the growth for each panel section is represented as 4.7 V output from the phototransistors. As summed up, depending on the robots success in their orientation and distance to the target during a poison attack, the total effect on a growth agglomerate results in a maximal output of 18.8 V. However, to reach high concentration values, simultaneous poison attacks by several robots are needed. The duration of an attack performed by a single robot is relatively short, since the robots are allowed to carry only a few poison dosages at a time. After computing the current level of biomass according to the growth model, the respective input level for the LED panels is updated. Contrary to phototransistor panels, each LED panel in a certain growth area shares the same control voltage, i.e. IR lighting is homogenous throughout the panel area.

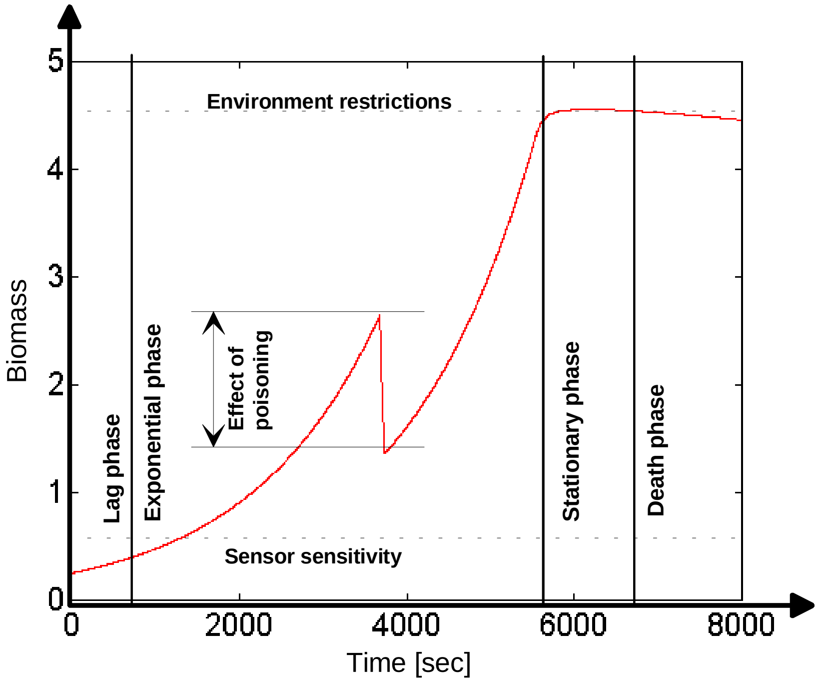


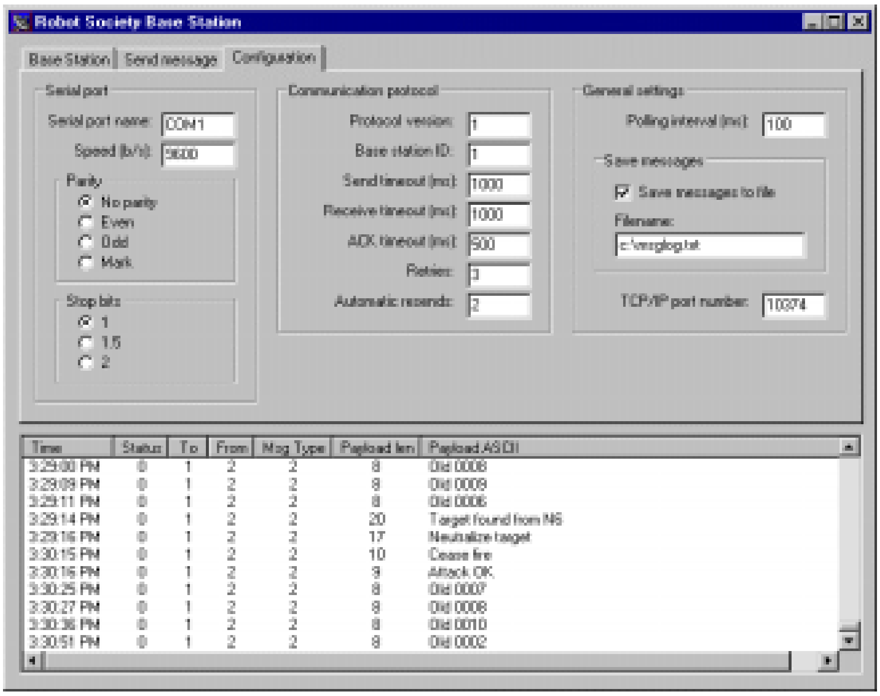
Figure 5.3 *Growth curve of the emulated biomass, featuring the four characteristic phases. The effect of an unsufficient poison attack is shown at about 3800 seconds.*

The emulated poison refilling and energy recharging station is implemented as the same type of IR LED panel area with a fixed lighting level in the bottom of the large tank.

5.1.3 User interface

The operator's communication station is an important part of the test environment system facilities. *Base station* software provides a user interface, which allows the operator to control the society and get on-line information from the robots. Figure 5.4 shows a screenshot from Base station software running in an NT workstation. This software features protocol parameter settings, different types of message transmissions, the monitoring of received messages, and the logging of all data to the files. The protocol used in communication is described in Section 4.4.2. Physically, the Base station communicates through a small half-duplex radio module of the same type that is used in the robots. The radio modem is connected to a PC via an RS-232 port. The TCP/IP connection to the user interface also enables the running of the programs from a distant location through the Internet.

Automatic mission control is a software client for Base station software. It allows pre-programmed mission controls for task execution, i.e. the messages will be automatically sent to robots at a given time (see Figure 5.5). The stack of unsent messages is in the lower frame, while transmitted commands appear in the upper section *(cursive print).*



Serial port

Serial port name: COM1

Speed (b/s): 9600

Parity: ● No parity ○ Even ○ Odd ○ Mark

Stop bits: ● 1 ○ 1.5 ○ 2

Communication protocol

Protocol version: 1

Base station ID: 1

Send timeout (ms): 1000

Receive timeout (ms): 1000

ACK timeout (ms): 500

Retries: 3

Automatic resends: 2

General settings

Polling interval (ms): 100

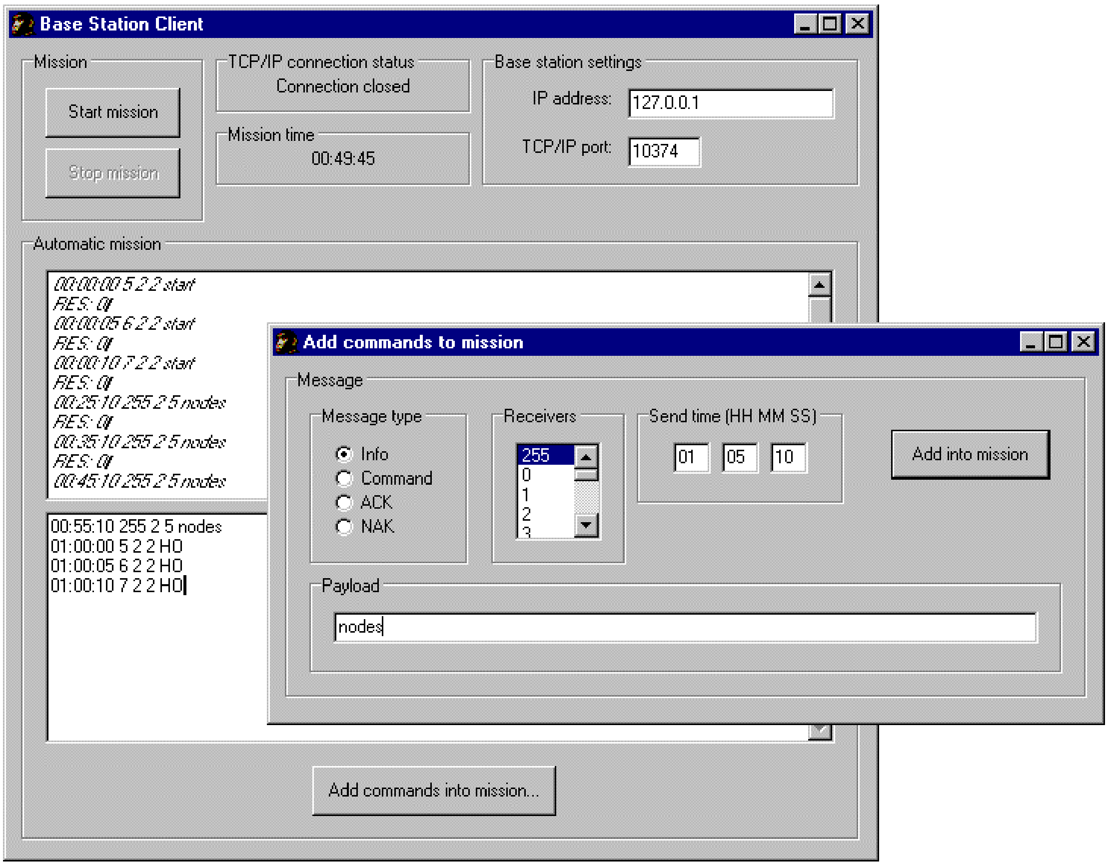
Save messages: ☑ Save messages to file

Filename: c:\msglog.txt

TCP/IP port number: 10374

Time	Status	To	From	Msg Type	Payload len	Payload ASCII
3:29:00 PM	0	1	2	2	8	Old 0008
3:29:09 PM	0	1	2	2	8	Old 0009
3:29:11 PM	0	1	2	2	8	Old 0006
3:29:14 PM	0	1	2	2	20	Target found from N6
3:29:16 PM	0	1	2	2	17	Neutralize target
3:30:15 PM	0	1	2	2	10	Cease fire
3:30:16 PM	0	1	2	2	9	Attack OK
3:30:25 PM	0	1	2	2	8	Old 0007
3:30:27 PM	0	1	2	2	8	Old 0008
3:30:36 PM	0	1	2	2	8	Old 0010
3:30:51 PM	0	1	2	2	8	Old 0002

Figure 5.4 *User interface running in an NT environment.*



TCP/IP connection status

Connection closed

Mission time

00:49:45

Base station settings

IP address: 127.0.0.1

TCP/IP port: 10374

Automatic mission

```
00:00:00 5 2 2 start
RES: 0
00:00:05 6 2 2 start
RES: 0
00:00:10 7 2 2 start
RES: 0
00:25:10 255 2 5 nodes
RES: 0
00:35:10 255 2 5 nodes
RES: 0
00:45:10 255 2 5 nodes
```

```
00:55:10 255 2 5 nodes
01:00:00 5 2 2 HO
01:00:05 6 2 2 HO
01:00:10 7 2 2 HO
```

Message type: ● Info ○ Command ○ ACK ○ NAK

Receivers: 255, 0, 1, 2, 3

Send time (HH MM SS): 01 05 10

Payload: nodes

Figure 5.5 *Automatic mission control for Base Station.*

Basically, it is also possible that the operator could guide the robots' task execution on a higher level. However, the user interface has not yet been integrated into the process control system. So far, the emphasis of the research work has been on the robots' fully autonomous functioning.

5.1.4 Preliminary simulator testing

Preliminary algorithm development, testing, and parameter estimation for the tasks were performed at first as a simulator study. This is well motivated, not only because the physical SUBMAR society was not yet in operation at the early stage of the development process, but principally, experimental work with a complex system consisting of several autonomous robots is very time consuming (...and may sometimes turn out to be a very frustrating experience indeed...). Nevertheless, the value and importance of real robot testing can never be underestimated.

The 3D simulator has been realized with Silicon Graphics C++ 4.0 and Open Inventor 2.1, which is an object-oriented 3D graphics toolkit providing an interface for graphics processors. The control architecture of the robots and the demo process with the complex flow dynamics are modeled as independent objects. The actual simulator controls these separate processes. Before starting the simulation, the properties of the robots can be adjusted as well as the environmental condition parameters. The simulator is running under Unix X-windows in the Silicon Graphics Indigo2 workstation. A series of snapshots from a simulation where the Robot Society performs a biomass removal mission is shown in Figures 5.6, 5.7, and 5.8. For more details about the simulator, see [Vainio et al., 1996].

Due to the simple environment sensing (i.e. only pressure and emulated optic algae detection) and precise modeling of the flow conditions of the demo process the "reality gap" between simulations and the real world does not grow too wide. The behavior of the robots scaled up pretty well and the results obtained from the simulator have proved to be quite comparable with the real robot experiments. In [Halme et al., 1999] and [Vainio et al., 2000a] simulated results are compared with results from real robot tests.

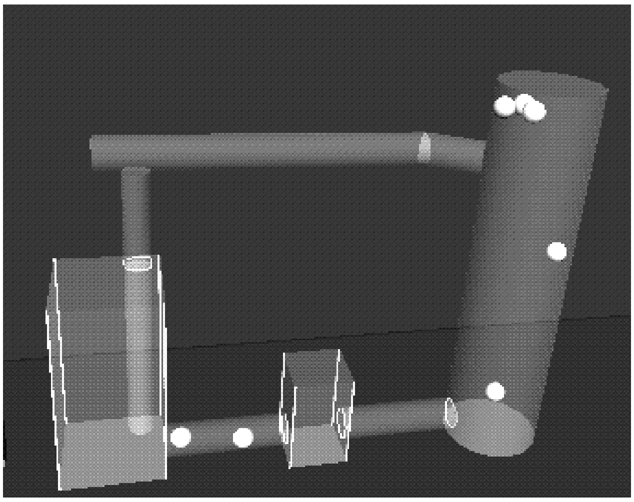


Figure 5.6 *Mission begins from the surface of the rounded tank.*

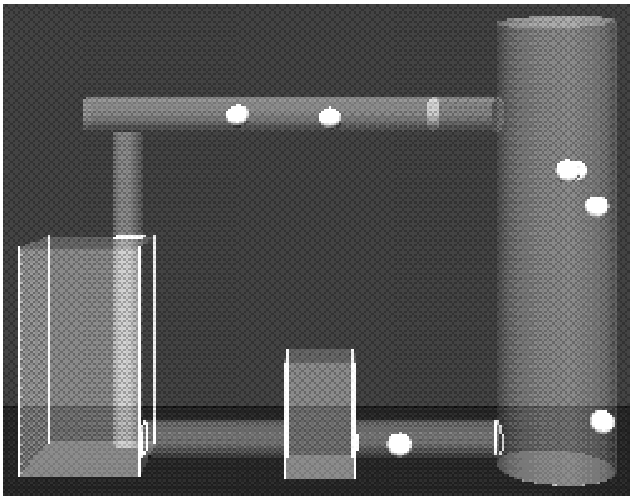


Figure 5.7 *The robots explore the process and map the growth areas.*

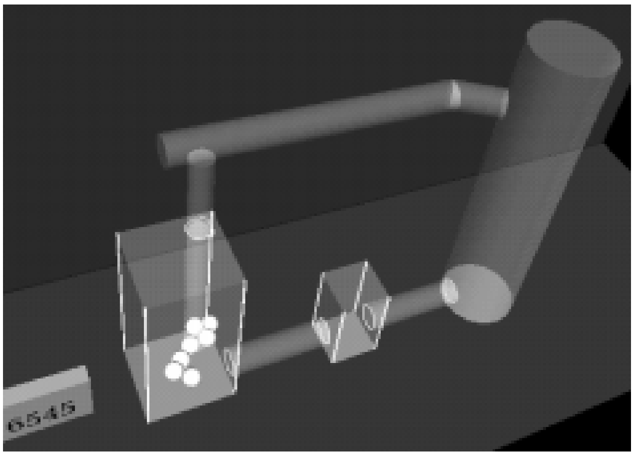


Figure 5.8 *The society is gathered together and looks ahead to a coordinated poison attack.*

5.2 Task definition

A dynamic, multitasking *explore and exploit* type of mission was specified for the SUBMAR society. Each robot runs two parallel tasks, called *Task A* and *Task B,* which are described in detail in the following sections. These tasks are implemented in the Task layer of the robot's control architecture in the form of an FSA representation, as discussed in Section 4.4.1.2.

5.2.1 Task A: Mapping, positioning, and navigation

Task A includes functions which enable dynamic environment mapping, as well as a robot's positioning and navigation facilities for a structured environment. In [Mataric 1991] a cognitive mapping system for an autonomous mobile robot was introduced. The landmarks were defined as combinations of the robot's motion and sensory inputs. The map produced by the robot contained *nodes* (i.e. landmarks) and topological *links* between different nodes, which indicate their spatial adjacency. With a related method, the structured underwater operation environment for SUBMAR robots is described by using a *strongly connected direct* *graph*. It is represented in the form of an adjacency matrix indicating the topology of the graph. After the initial mapping of the environment, by following this graph the robot is capable to a rough areal positioning and navigation to these locations. This system is called the *feature based positioning and navigation system*.

According to the desired minimalist approach, initial mapping of an unknown environment (as well as positioning) is based on the processing of a single variable, namely pressure. Other quantities, such as acceleration data or distance information, could be utilized in a feature based environment mapping as well. The pressure value and its history in a short time window are continuously monitored to detect events (i.e. nodes) when the robot's motion character changes. Connections between the detected nodes are called links. Four different vertical motion types can be distinguished: (1) motion changes from a certain level in a downwards movement, (2) from a downward motion to a certain level, (3) from a level upwards, and (4) upwards to a level, as illustrated in Figure 5.9. The data obtained this way is naturally limited and open to errors. As a solution, an adaptive method is used.

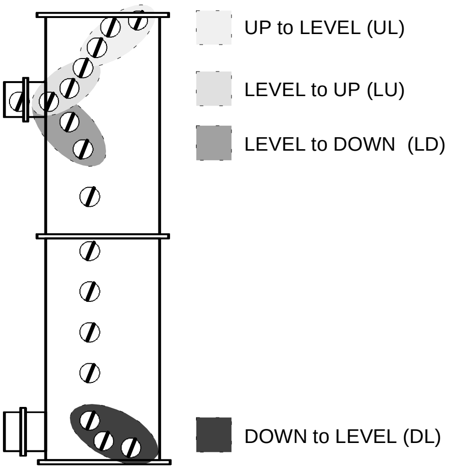


Figure 5.9 *The environment mapping is based on characteristic motion features in certain locations (nodes) and connections between these nodes (links).*

In [Yamauchi 1995], a concept called APN (Adaptive Place Network) was introduced. This provided a spatial representation and learning capability for a mobile autonomous robot. A modified version of this method is implemented into SUBMAR robots and described briefly in the following: when a new link is created it is also assigned a confidence value $c \in [0,1]$. This value estimates the reliability of the link, i.e. does it exist or is it a sort of erroneous detection due to collisions between society members or some other reason. At the beginning, a new link is given a certain initial value as its confidence, value c. If the robot travels through a link then the value of that link is increased with the following equation:

$$c_{t+1} = \lambda + (1-\lambda) * c_t \qquad \text{(Eq.5.3)}$$

where λ is the learning rate. After a certain number of nodes have been detected, the values of all links are reduced according to the following formula:

$$c_{t+1} = (1-\lambda) * c_t \qquad \text{(Eq.5.4)}$$

When the confidence value c goes below a certain threshold, the link disappears from the adjacency matrix. If all links connecting the node to the graph are deleted, then the node is also removed from the graph. Collisions with other members create nodes which, however, automatically fade away from the graph. In order to find all the nodes needed, i.e. the process compartments having difficult access, the robots need to explore the environment actively.

At a certain phase, the mapping described above reaches a stabile form, where only small temporary changes emerge. The maturation of the map can be detected by following the number of new nodes vs. old modes. In a matured stable form, the map is dominated by old nodes, while new nodes are detected only occasionally. The size of the map stays within reasonable limits due to the reinforcement features. To allow coherent cooperative functioning, the members of the robot society should share the same map. There are various methods available to perform the fusion of information from the robots to produce a common representation of the environment, called the Common Basic Map (CBM). The CBM can be the result of autonomous information sharing through inter-robot communication, or it can be done with the help of the system operator. In Figure 5.10 the CBM adjacency matrix representation used in the experiments is illustrated at the top of the demo process layout. Development of the environment mapping algorithms and feature based positioning system are presented in [Vainio et al., 1996] and [Halme et al., 1996].

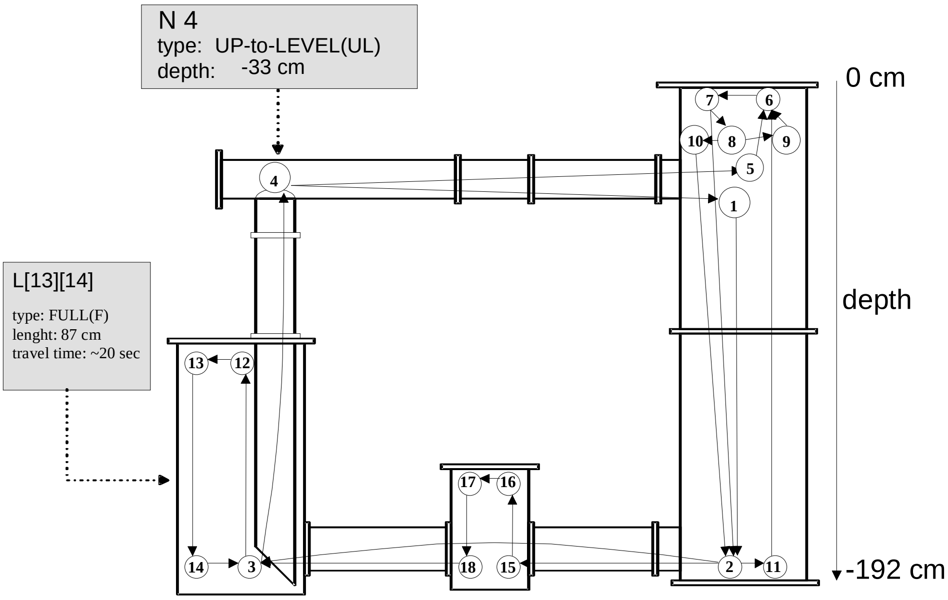


Figure 5.10 *Numbered locations drawn to the demo process layout are the nodes found by the feature based positioning system. The nodes are characterized by their type and depth, as shown in node 4. Links contain information related to the motion type and distance, for example, see the link connecting nodes 13 and 14.*

After the initial mapping process the CBM is used for robot navigation. Since the CBM is in the form of a strongly directed graph, it means that from each node there is an access to all other nodes. Path planning is performed by using Floyd's algorithm (see for instance [Sedgewick 1988]) to calculate the shortest path (node trail) between the current node and the destination node. Then, by comparing the depth information of the nodes to be passed through on the node trail to the desired destination, the actions of the diving tanks are decided.

As an example, a navigation case from node 6 to node 12 can be considered (see Figure 5.10). The shortest node trail contains nodes 6,7,2,3, and 12. Now, by checking the links and tracing backwards, the robot knows when to use its tank actuators. In this case, it should dive at first to leave node 6 and move upwards after node 2 to reach node 12. However, the robot can fail in node 3, if it drifts to the intake flow of the vertical pipe. Then the robot arrives at node 4 instead of the destination node 12, and it has to re-plan its navigation to take a new attempt. Because of the robots' partly stochastic behavior due to the very limited maneuverability, they sometimes loose the trail or detect otherwise erroneous nodes. Therefore, it may take a couple of attempts to achieve the destination. Nevertheless, extensive testing has proved that the feature based positioning and navigation system is a very robust and reliable method if certain limitations can be omitted. Mapping, positioning, and navigation algorithms with detailed flowcharts, as well as complete test results are presented in [Vainio 1999].

Task A is implemented into the robot's Task layer as an FSA with four states: *make map* (initial environment mapping), *fix map* (producing the CBM), *use map* (navigation), and *check map* (frequent checking of the map in the case of a dynamic environment).

5.2.2 Task B: Emulated biomass detection and removal

Task B consists of functions related to the detection and removal of the emulated biomass growth in the demo process environment. The spatially distributed targets, i.e. emulated algae growth spots, have a dynamic behavior; they grow and get stronger according to their growth model. If a target is not completely destroyed, i.e. poisoned, it will continue its growth. This leads to an interesting problem: what is the optimal strategy for the society to accomplish this kind of dynamic task in the minimum of time? Should the society at first try to locate all the algae growth locations before beginning to poison them, or should it poison immediately once the first growth area has been detected? Other possible optimization criteria would be the minimization of energy consumption or poison usage.

A robot gets feedback from its actions directly from its sensors, and indirectly through inter-robot communication. Feedback from task execution is necessary for the robot to enable self-evaluation and optimization of its functioning. Autonomously coordinated collective poisoning of these dynamically growing spots requires not only adaptivity from single robot members (based on Task layer rules), but also self-configuration at the society level (Cooperative layer). This means, for example, the forming of sub-groups to intensify some local actions.

As a practical implementation into the robots' Task layer, three alternative strategies form the FSA states for Task B: *attack the closest algae growth*, *attack the largest algae growth*, and *attack the smallest algae growth*. However, these are just examples of possible strategies; the research concerning various strategies in cooperative functioning is just in its initial phase. For example, in a more complex scenario having a larger number of targets, "the fastest growing" and "the fastest dying" strategies might prove profitable, as well as more strict organization of the robots into subgroups.

5.3 Experiment series I: Cooperation in distributed task execution

In the first experiment series, the cooperative functioning of the robots was studied and evaluated. The main issue was to find out how the performance of the society changes when:

1. The volume of the society, i.e. the number of robot members, is varied
2. Inter-robot communication (IRC) is allowed or banned

Systematic testing was carried out with societies having 3 or 5 robot members, both with and without inter-robot communication. The tasks for the mission were explained in Sections 5.2. and 5.1.2. The maximal duration for each test run is set as one hour and the robots are assumed to have completed the CBM representation of the environment. Two target algae growth areas are set active. For each test run, development curves for the biomass volume and respective successful poison releases for the growth areas are recorded, as shown in Figure 5.11. Algae growth volume and poison concentration values are expressed in Volts as a function of time.

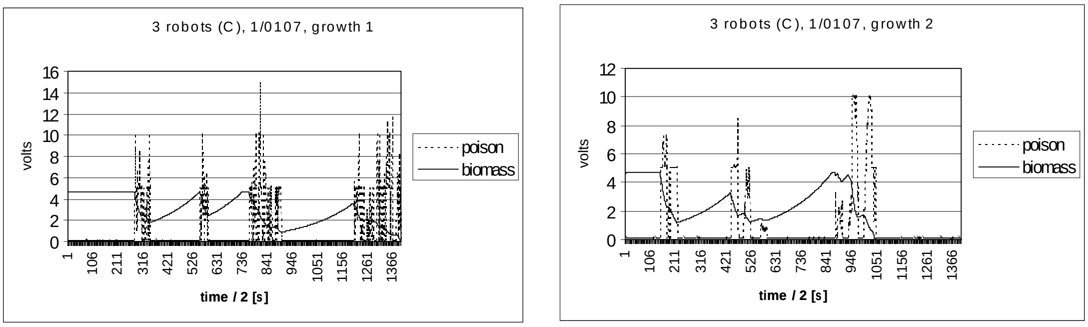


Figure 5.11 *An example of test results produced by one particular experiment run. After one hour of operation, growth location 2 is dead, while growth location 1 is about to be eliminated.*

To compare the overall result executed by the robots in each run in terms of the total volume of living biomass, the sum of growth volumes in locations 1 and 2 was calculated and plotted (see Figure 5.12).

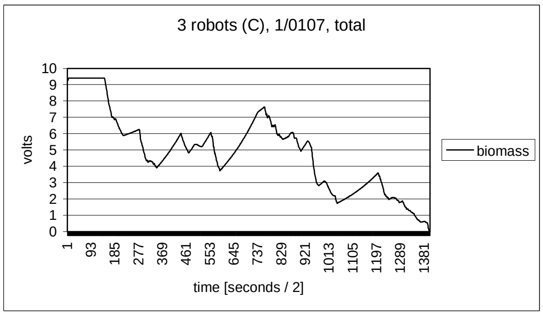


Figure 5.12 *Exemplary summation curve for the total biomass volume.*

5.3.1 Single robot tests

The overall average performance for separate setups, i.e. 3 or 5 robots, communication active or not, was calculated simply by taking an average of the set of the same type of test runs. As a reference to the actual multi-robot tests, a single robot case was evaluated with five runs at first. The results can be seen in Figure 5.13, which demonstrates clearly that mission completion is impossible for a single robot. Detailed test results are shown in Appendix G.

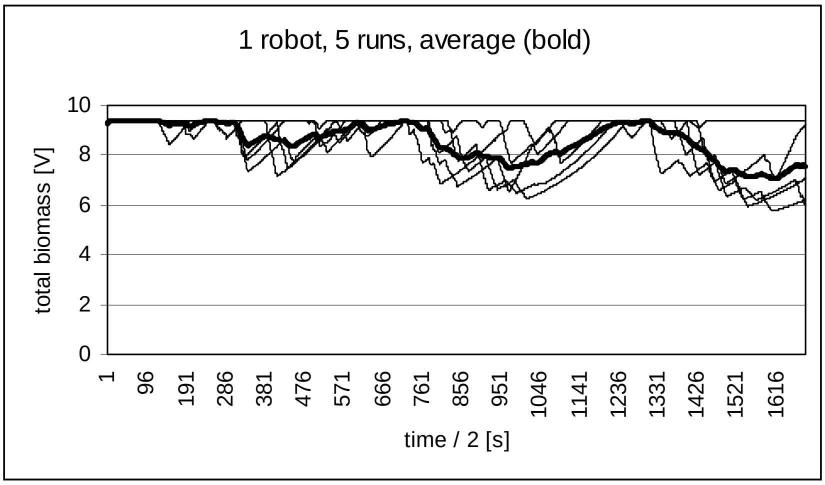


Figure 5.13 *Five attempts performed by a single robot. The average result curve is plotted as a bold line.*

5.3.2 Tests with 3 robots

The same experiment was executed with 3 robots, but inter-robot communication was not allowed (NC), see Figure 5.14 and Appendix H for results. The overall average result ended at approximately 1.7 Volts.

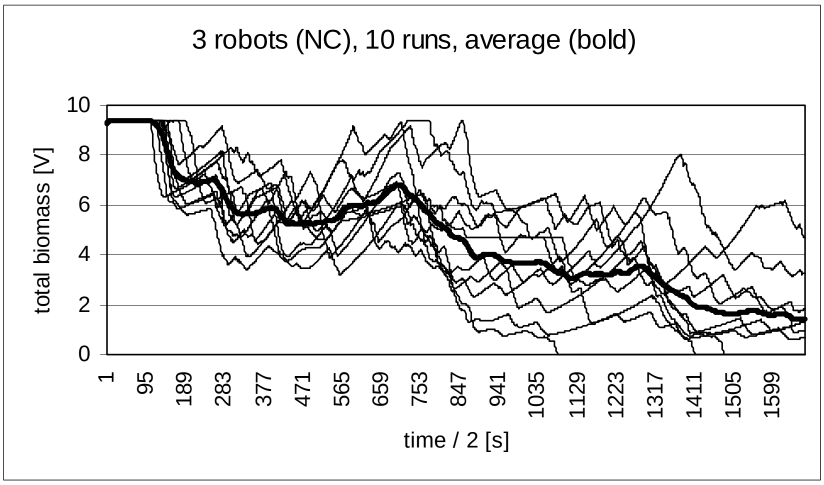


Figure 5.14 *The total biomass removal curves for 3 robots. Out of 10 test runs, the non-communicating society was able to remove the growth completely before mission time was over three times.*

Next, the amount of robot members was kept unchanged, while basic inter-robot communication (C-type) was allowed. The respective results can be seen in

Figure 5.15 and Appendix I. With this cooperative setup, the overall average result ended at less than 1 Volt. Figure 5.16 shows the SUBMAR society in action.

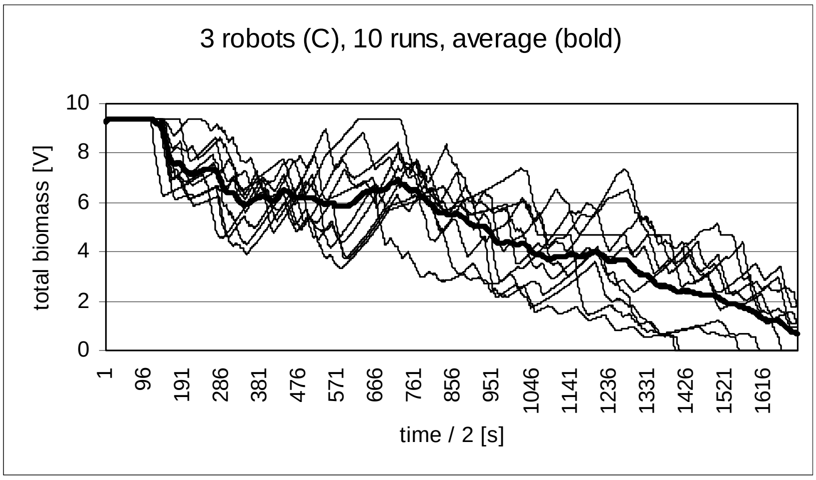


Figure 5.15 *Total biomass decrease as a result of 3 robots cooperating. In half of 10 test runs, the small society was able to accomplish the mission.*

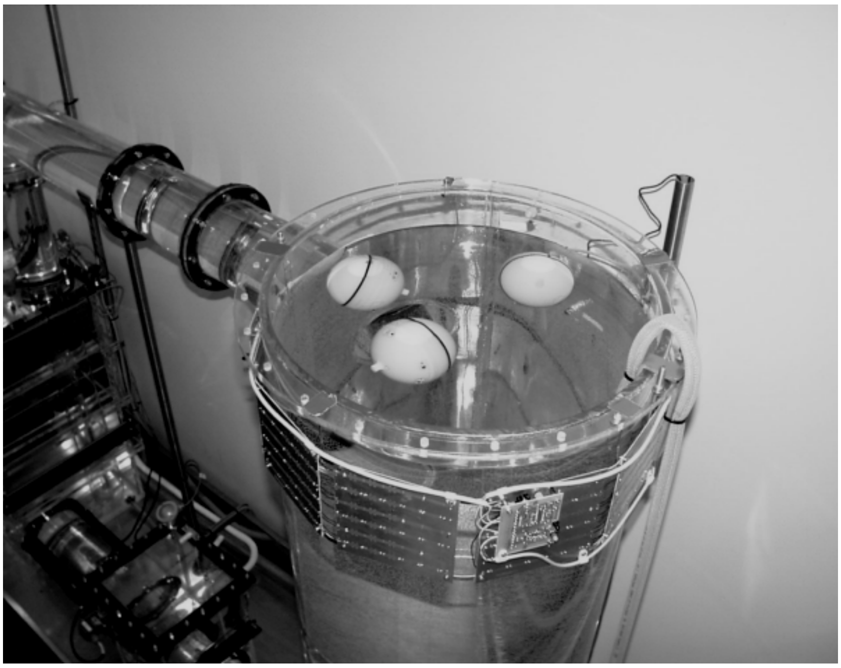


Figure 5.16 *A small society of 3 robots performing a simultaneous poisoning attack against "cyber algae" in location 1. Emulated biomass growth is visible around the transparent tank.*

5.3.3 Tests with 5 robots

The experiments were continued by adding two more robot members to the group, again, at first without communication (NC). As a result, each of the 10 test runs were successfully terminated (see Figure 5.17). The average mission completion time in this case was about 42 minutes. See Appendix J for more detailed results.

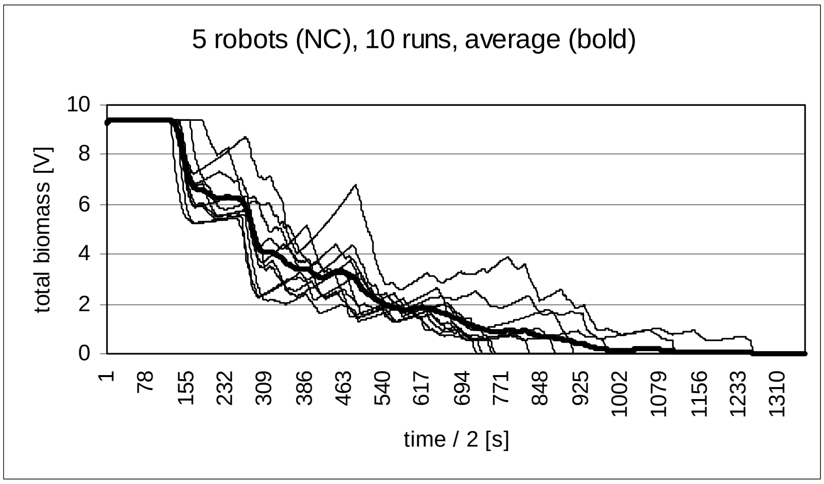


Figure 5.17 *Five non-communicating robots are able to accomplish the task in every run. The average curve ends at 1267 time units.*

The non-communicating tests were followed by communicative variation with otherwise the same settings. The results are illustrated in Figure 5.18 and Appendix K.

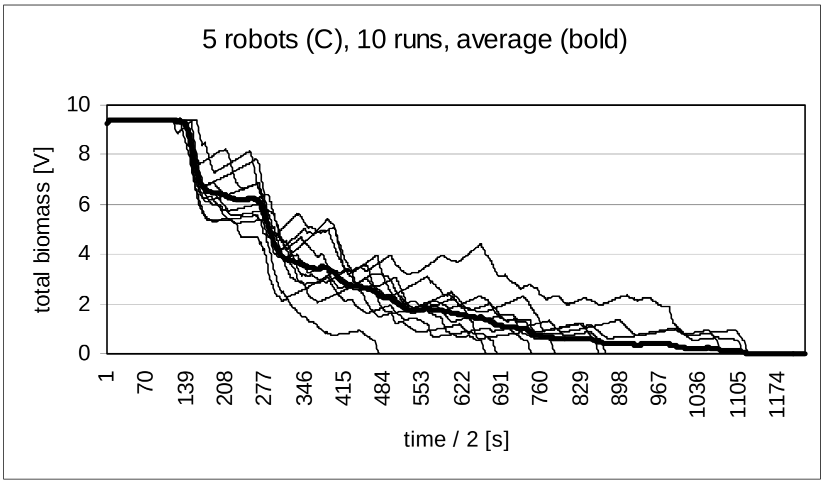


Figure 5.18 *The performance curve for 5 robots with basic communication active. Now the average curve ends at 1225 time units.*

With the basic C-type IRC active, the average result was only slightly better compared to the case without mutual communication. To be exact, the advance in mission completion was only less than 1.5 minutes. The amount of information exchanged by the robots with C-type IRC is rather minimal. It only includes the success rate value for the performed strategy. The value is broadcast after a robot has completed a poison attack. In the tests with more extensive CC-type IRC, in addition to C-type, the algae levels sensed by a robot are broadcast before and after each poison attack. Collective information sharing concerning algae measurement values ensures more accurate measurements, which leads the robots to choose correct and coherent strategies. This improves the performance of the whole society, as seen in Figure 5.19. See also Appendix L for these results.

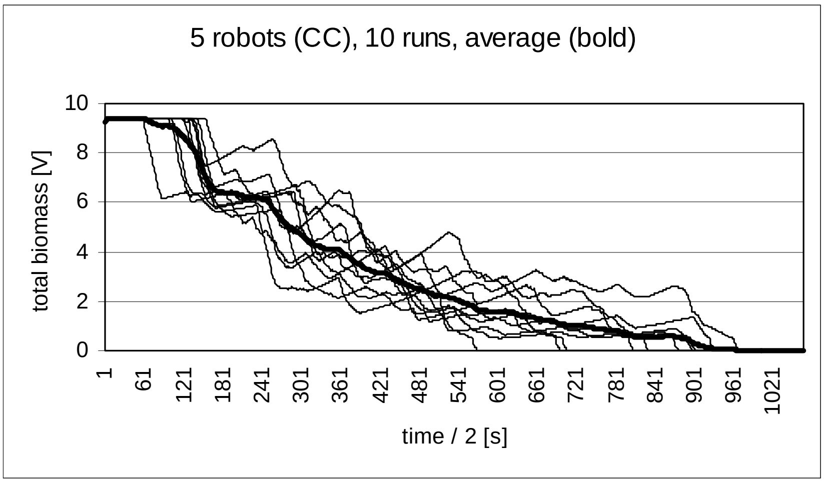


Figure 5.19 *The CC-type communication clearly improves the performance of the society. On average, the mission is completed in 977 time units.*

The CC-type communication improves the average result, i.e. mission completion time, by more than 9 minutes when compared to the non-communicative case, while the advance is approximately 8 minutes to the C-type communication. It is very clear that the relevance of shared information for the task execution is crucial.

Once the correct type of information is shared by the robots, one might think that the better the IRC success rate, the faster the mission completion. The amount of IRC broadcasting and receiving events were recorded in the log files of each robot during the 5 robot case tests. Based on this data, the IRC success rate percentages were calculated for each robot, i.e. the number of received IRC messages by a certain robot was divided by the total number of broadcast IRC in a particular run. The average of these values represent the IRC success rate of the whole society in that run. However, surprisingly, no negative correlation between the IRC success rate and the respective mission completion times can be stated (see Figure 5.20).

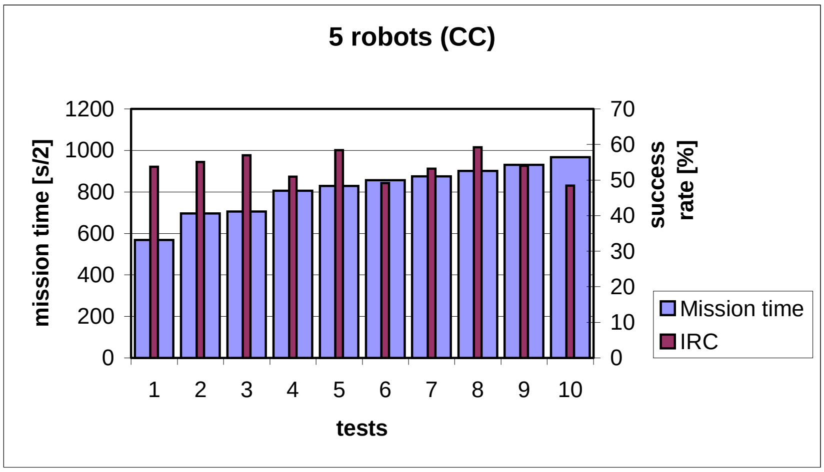


Figure 5.20 *Mission completion times with CC-type IRC are compared to respective IRC success rate values. No statistical correlation could be found by applying the T-test.*

The specified IRC success rate values verify the throughput for the communication system in the demo process environment. Along with IRC, the respective ORC (Operator-to-Robot Communication) figures were also recorded. Both results are illustrated in Figure 5.21. On average, the success rates for IRC messages is 53.9 %, and for ORC messages 50.2 %. No correlation between IRC and ORC throughput figures was found, which proves that the noise and interference disrupting the communication in the demo process environment is purely coincidental by nature.

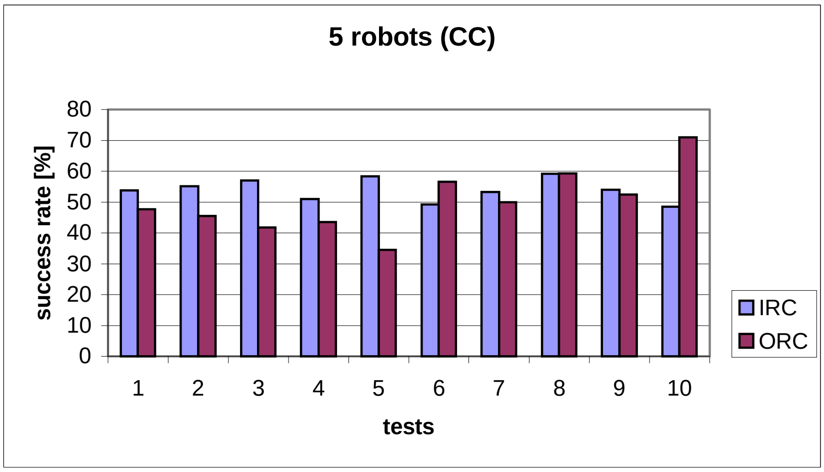


Figure 5.21 *IRC and ORC success rate values in comparison.*

5.3.4 Summary

To summarize the results from Experiment series I, the average performance curves from all 6 different test setups are illustrated in Figure 5.22. These curves represent 55 individual test runs with the SUBMAR society.

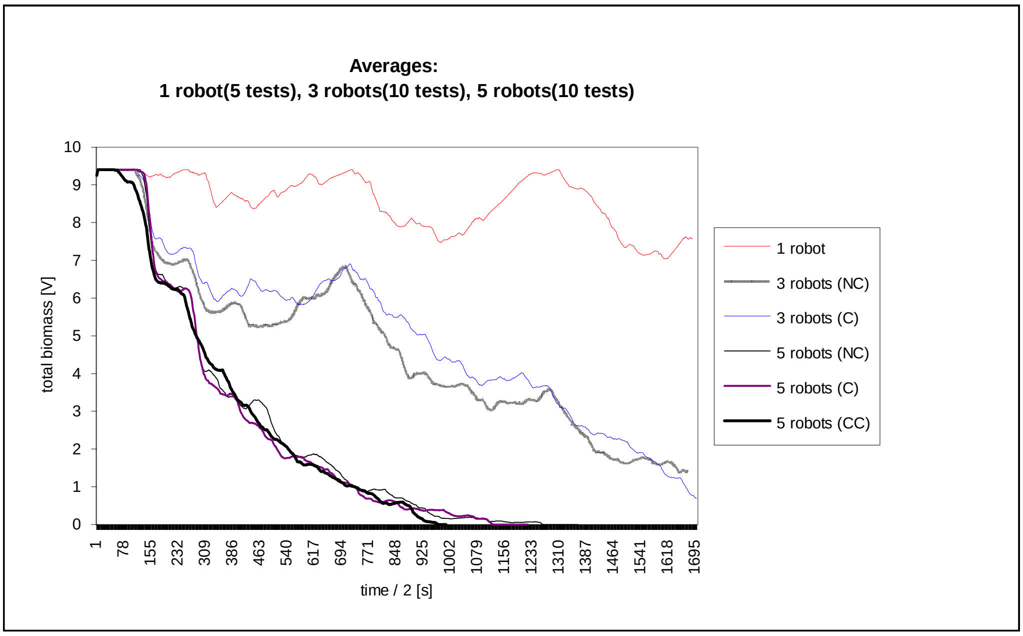


Figure 5.22 *Summation of the mission time curves from Experiment series I. The differences in performance between 1 and 3 robots and 3 and 5 robots are very clear.*

The effect caused by varying the number of robots becomes very clear. The more robots, the faster the mission completion. To what extent though remains open. Once the number of robots exceeds a certain limit, the results begin to decline due to the competition for space and resources. The simulator studies [Halme et al., 1999] suggested that the optimal number of robots for these tasks in this environment would be 5. During the testing there were 7 robots in a fully operational state, but unfortunately some robots suffered occasionally from pressure sensor calibration problems requiring constant attention. Therefore, the maximal number of robots in the tests was limited to 5.

The other main objective for this first experiment series was to *verify the effect of inter-robot communication* on the overall performance. On average, the CC-type IRC provided perhaps an unexpectedly slight, although still significant, increase (21.4 % in the 5 robot case) to the collective performance of the society when mission completion times were compared with the non-communicative case. The meaning of the results from Experiment series I concerning the decision-making mechanisms of the control architecture of the Robot Society, and especially the choice of strategies in Task B, are analyzed in detail in [Vainio 1999]. In spite of this, the relevance of IRC for the overall performance of the society could not be stated comprehensively with this test series.

5.4 Experiment series II: Communication and collective consciousness of the society

The second test series was performed to bring deeper understanding to the meaning of inter-robot communication in dynamic multi-sensor measurements. The key question is *what factors affect the dynamics and accuracy in the development of the collective consciousness*. This was analyzed with a two-stage step response test. In these tests, robot functioning and information processing is kept exactly the same as in the first experiment series, while the behavior of the target biomass growth spots is changed as a fixed two-stage step function as a reference for the robots. Therefore, the robots actions against the targets have no effect on the preprogrammed biomass level. Each experiment run takes an hour. To monitor the state and development of the collective consciousness of the robots, the biomass levels for the targets estimated by each robot are recorded twice per minute.

For the first 15 minutes, the biomass reference level is at its maximum, i.e. 4.5 Volts. This phase is continued by a minimal (non-zero) biomass level of 0.7 Volts. The last 15 minutes are again at maximal level. The maximal biomass value corresponds to approximately 950 units measured by the robots. Each test run produces the curves for the assumed biomass level from each robot for the two target locations. To describe the collective estimate achieved by the society, the average of these individual curves for both target areas are also plotted (see Figure 5.23).

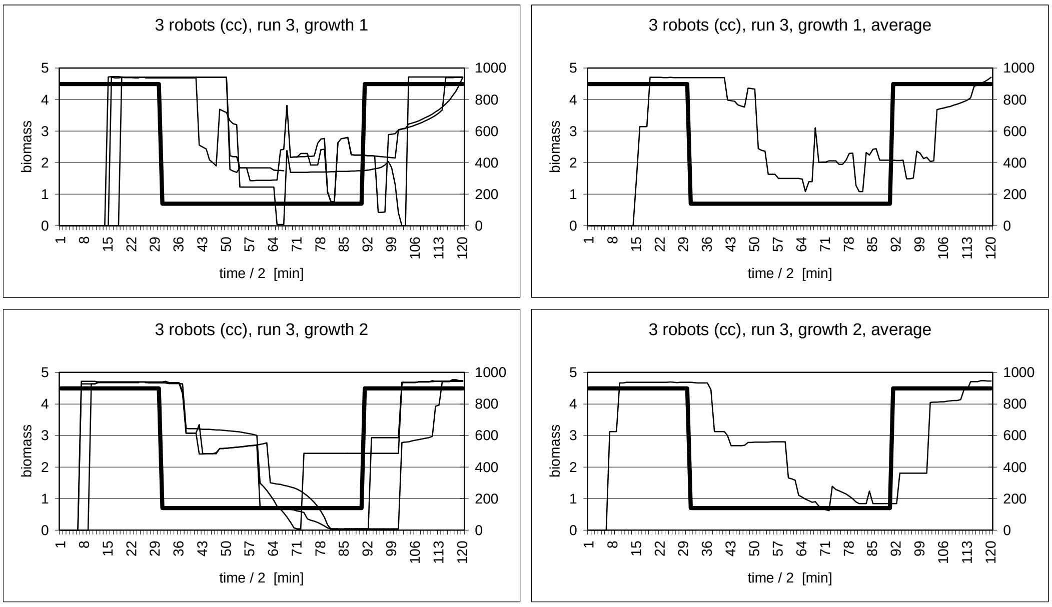


Figure 5.23 *An example of test results from one particular experiment run. The reference curve is plotted in bold.*

Again, the test series were performed with 3 and 5 robots, both with and without inter-robot communication. In tests where IRC was applied, the CC-type communication was used.

5.4.1 Tests with 3 robots

At first, the experiment was carried out with 3 non-communicating robots. Results from 10 runs are shown in Figure 5.24. In the pictures on the left hand side, each curve represents the average of a particular run. Furthermore, the bold line in all pictures is the average of those 10 runs. The reference curve is also visible.

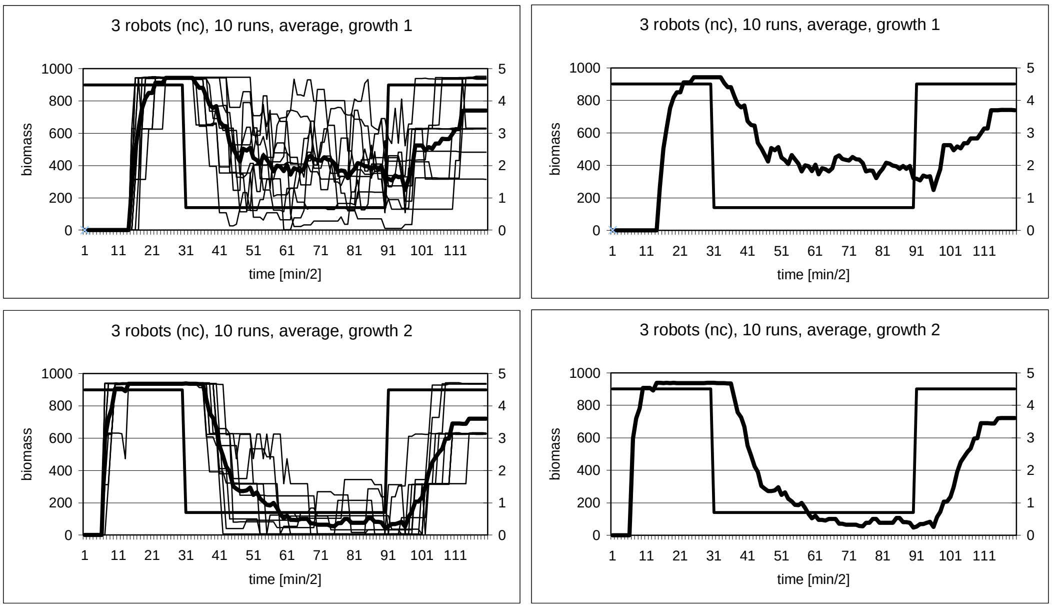


Figure 5.24 *The results from the 3 robot non-IRC case show that in most runs, the detection of the second step is delayed and not complete for a given mission time.*

Then, the same experiment was tested with IRC allowed. The results are presented in Figure 5.25.

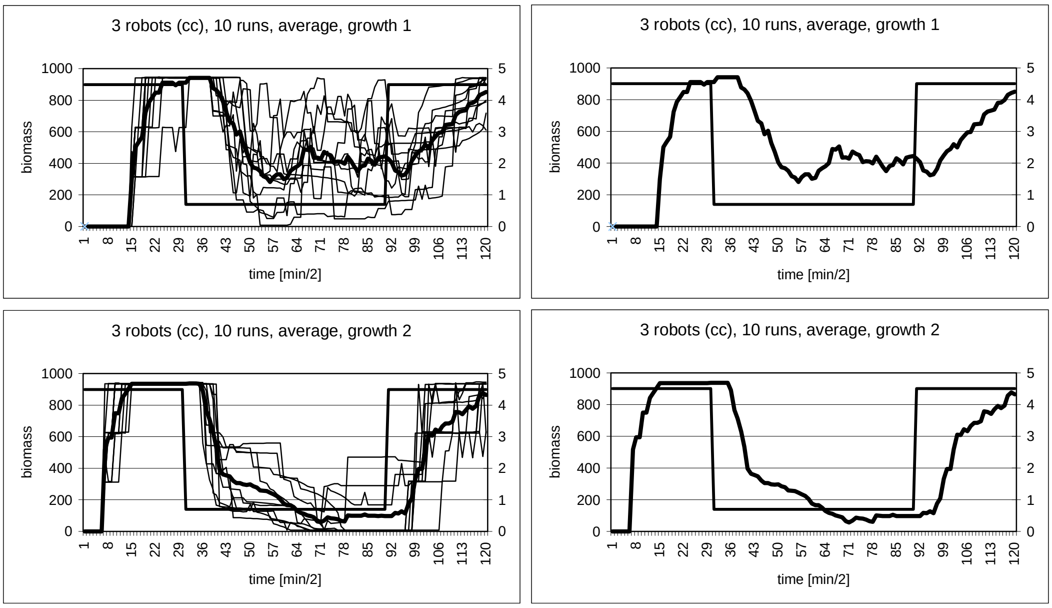


Figure 5.25 *Three robots with IRC, 10 runs. Complete detection of the second step is almost achieved in the last minutes of the mission time.*

5.4.2 Tests with 5 robots

The tests were continued with 5 robot cases. In Figure 5.26, the non-IRC case is illustrated.

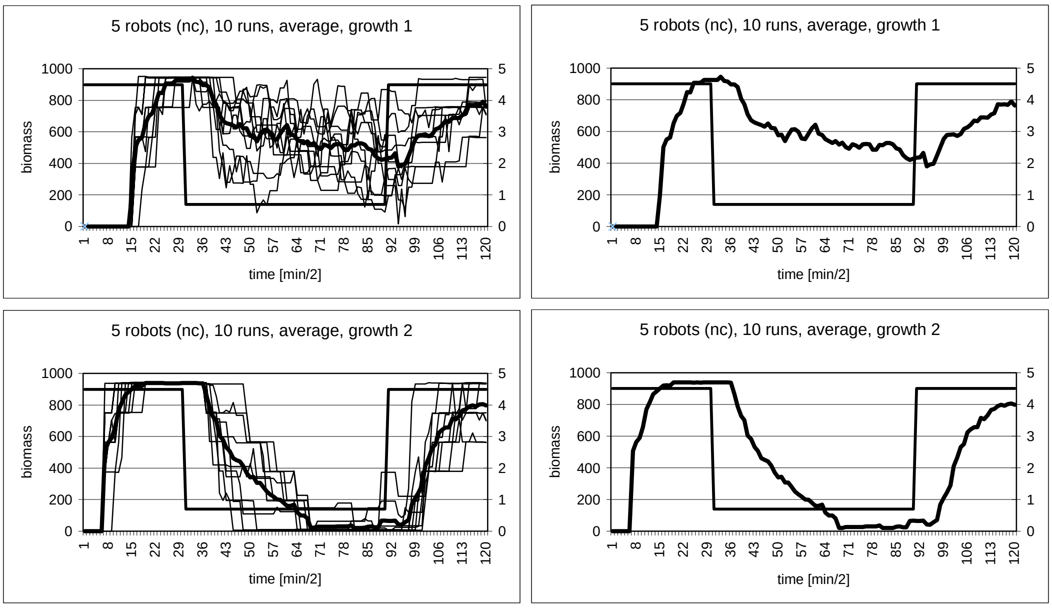


Figure 5.26 *Five robot cases without IRC, 10 runs. Again, the second step is not completely detected, and in spot 2 the estimated values go to zero for a long time.*

Finally, 5 robots were tested with IRC allowed, and the results from those 10 runs are shown in Figure 5.27.

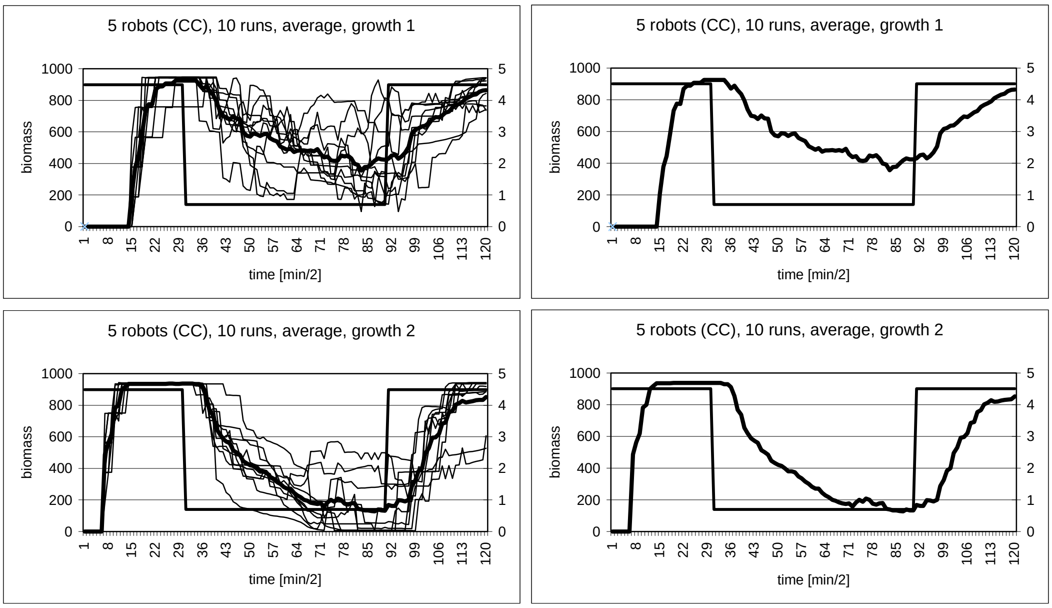


Figure 5.27 *IRC-case, 5 robots. The second step is quite well recognized, although, in growth 2 two individual runs end at an exceptionally low level.*

5.4.3 Summary

At first glance, the curves for different cases resemble each other quite a lot. The measurement task for the robots became very difficult to carry out reliably, since the varying distance to the target strongly affect the acquired value. Even if special measurement procedures were always used to acquire the most correct, i.e. largest, measurement value, the results are still very inaccurate and sometimes even misleading.

However, once these results are analyzed in a more detailed way, different characteristics of the two target areas have to be noted. In *growth area number 1*, there exists some turbulence in the water flow. This means that the robots change their orientation and position during the measurement procedure, which yields more reliable measurement values. In contrast, in *growth area number 2*, where the water stands still, greater measurement errors are more likely to occur. In Figure 5.28, the average correlation between the biomass reference curve and the respective collectively assumed biomass levels in various cases are shown.

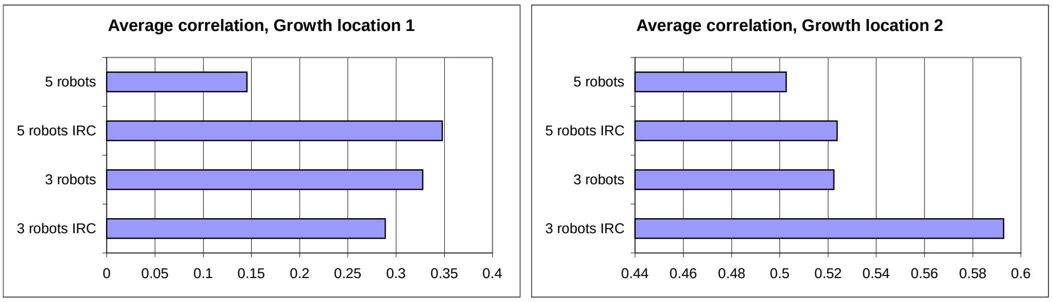


Figure 5.28 *Average correlation coefficients, 10 runs in each case.*

As can be seen from the results, for growth area 1, the 5 robot case with IRC produces the best correlation. For the more difficult area, location 2, the best correlation results are archived surprisingly by 3 robots with IRC. Correlation coefficients are relatively low, although all values are statistically notable according to the T-test (α=0.05) except the 5 robot case without IRC at location 1. One main reason for the low level of correlation is the fact that the reference curve and the measurements are basically non-scaled. However, a linear match where 1 Volt corresponds to 200 units for the robots' measurements yields a satisfactory match. Because of various characteristics in growth locations, the performance curves and figures between different growth areas cannot be directly compared.

Then, in the same manner, standard deviations (STD) for the robots' measurements are calculated and the results from the 10 runs averaged. The results are illustrated in Figure 5.29. In location 1, as one might intuitively expect, the STDs are the smallest for the IRC-cases when compared with non-IRC cases. In other words, once the measurements provide reliable results, the smallest STD value verifies the most effective setup. For some unknown reason, in location 2, in the cases where 3 robots were applied with IRC, the largest STD for the collectively acquired information was developed. In this case, where measurements are known to be very unreliable, this explains the best result in the respective correlation analysis. For the other setups, the measured and broadcast information contained more uniform, but incorrect values. *One explanation can be that for this area, 5 robots were already too large population, shadowing and blocking out each other during the IR-light measurement procedure.*

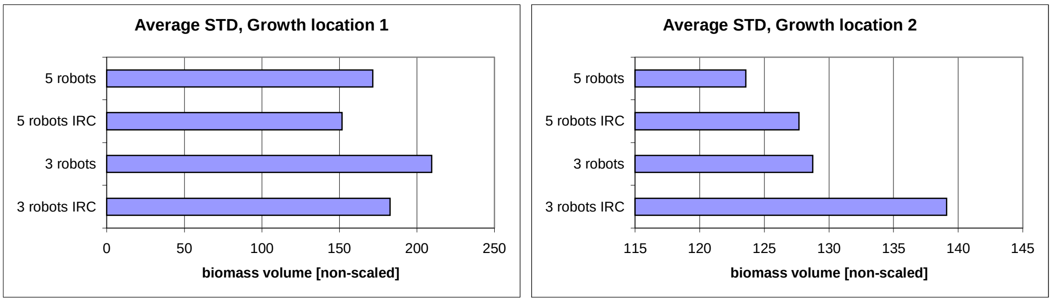


Figure 5.29 *Averaged standard deviations for the measurements.*

5.5 Conclusions

Two different extensive test series have been carried out to verify the functioning of the multi-robot system designed and its control architecture while executing a distributed multi-task mission. Altogether, data from 95 experiment runs with physical robots have been recorded, documented, and analyzed. An optimally performed collective task execution consists of the right combination of perception, actuation, and communication. The relations and parametrization of these elements are highly case-dependent. Therefore, the results presented apply only to the given test environment and tasks; generalization of the results achieved requires extra precaution.

The Experiment series I was carried out to analyze the performance of the SUBMAR society by using a different number of robots with various communication setups. These tests were followed by Experiment series II, since the primary effect of inter-robot communication required further analysis. *As a whole, the results from these tests indicate that basically the system functions well, pretty much in an expected way. The performance of the system can be upgraded up to its saturation level by increasing the number of robots and their communicative interactions. This rather intuitive result assumes that the available and shared measurement information is reliable enough.* On the other hand, clear system robustness against sensor errors was also demonstrated, although poor quality measurements diminished the obvious advantages of inter-robot communication. From the point of the development in collective consciousness, the quality and reliability of broadcast IRC information is essential.

When analyzed task-wise, Task A, which consists of environment mapping, positioning, and navigation procedures, proved to work very reliably giving a rough areal accuracy in the closed structured environment used in the tests. When it comes to the actual utility task, Task B, it is clear that better results could have been achieved if the functioning of the system had been more optimized for the particular properties of the demo process. This applies to the transitions in state between strategies and biomass measurement procedures in particular. As implemented, the strategies in Task B could obviously better handle much more complicated missions having a larger number of target areas and robots. However, the motivation for these Robot Society studies has been rather to test and develop more generic than strictly application addressed ideas and structures.

In a complex autonomous system having reactive components, when the overall state of the system cannot be predicted unambiguously, there is always a risk or chance to produce completely unintended actions as a side effect. These type of sometimes useful *emergent features* did not really occur while testing the SUBMAR society, although interesting and unexpected phenomena were seen, as shown in Figure 5.30. Nevertheless, to guarantee safe autonomous operation in complex practical installations, the systems designer should always be aware of potential emergent behaviors and ensure manual emergency control over the system in every imaginable situation.

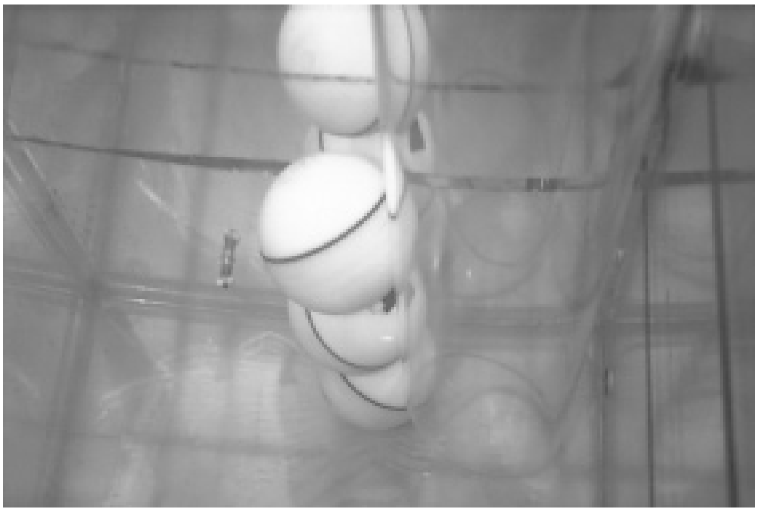


Figure 5.30 *Unexpected self-organization. Three robot members forming a stack.*

Chapter 6

Technological considerations

6.1 Enhancements and suggestions for implementation

This section discusses various technological considerations to enhance the functional properties of the sensor/actuator robots with existing technology and components. Additional sensors and actuators, more efficient methods for communication and positioning, as well as alternative means to perform active horizontal motion would enable a wide range of various real-world applications and upgraded performance.

6.1.1 Sensors

For many applications the key question is to find a suitable sensor for the quantity measured. In the case of small mobile robotic devices, such as SUBMARs, the sensor should be small enough to fit into a SUBMAR casing, but still meet the specified needs in terms of accuracy, resolution, dynamics, repeatability, and stability. Nowadays, novel small-sized high-quality sensor products are emerging from a fast developing microtechnology area, which is under an extensive research boom. As mentioned in Chapter 4, the functioning of *internal and external temperature-, pressure-, orientation-,* and *conductivity sensors* has been verified already. In the following, some other possible sensors applicable to SUBMAR robots are discussed.

Acceleration sensors mounted axially in an orthogonal XYZ-configuration could provide useful additional information for a feature-based positioning system, especially if the robot's horizontal-plane orientation can be maintained. Acceleration data can also serve a robot's self-diagnostics by detecting collisions, shocks, or vibrations which are known to be too excessive for the mechanical structure. To set up a complete Inertial Measurement Unit (IMU) for inertial navigation purposes, in addition to acceleration sensors, three orthogonal *gyros* are needed to measure angular rates. Arbitrary motion consists of six-degrees-of-freedom: three for translation and another three for rotation. However, in the context of omnidirectional and spinning motion characteristics, the actual benefits of the gyros are questionable, and remain untested. Because of the cumulative nature of errors in gyro-based systems, additional and especially the absolute type of sensor information is needed. Even the state-of-the-art small micromechanically manufactured piezo-electric gyros are still relatively inaccurate for navigational purposes. The *compass heading* from an electric magnetometer compass corrected with tilt-angle information from *inclinometers* can be used to provide an absolute type of information from the robot's orientation, at least in non-metallic environments. In some cases and for proximity sensing, *sonar* could be applied. The detection of the near-field environment by electromagnetic means might provide useful information in certain cases. A *speed sensor* would be useful both as a navigational aid and as a mean to get information from prevailing flow conditions. However, if the robot mainly drifts along the flow and spins omnidirectionally, true speed measurement is not straightforward to arrange.

In the monitoring of different types of biological processes, like environmental water quality analysis or fermentation processes, the amount of *dissolved oxygen*, *redox potential*, and *pH value* are important quantities. However, the size of those sensors is reasonably large and service-life short. Luckily, sensor technology is a very fast developing area and there are already some ion-selective semiconductor technology based sensors emerging on the market. *Turbidity, irradiance, photo-fluorescence*, and *particle size* are quantities which can be measured optically. In those measurements, the level of light transmittance or back-scattering is measured in various ways. Semiconductor components can be used, which basically allows small-sized sensor devices. The *viscosity* of the surrounding liquid can be calculated from vertical velocity, i.e. from a pressure signal, while diving.

A *video camera* for visual inspection and navigational aids is a tempting idea in an AUV. Nowadays, CCD video cameras come in surprisingly small sizes with low light requirements. On board on-line image-processing would require a high computational capacity from the robot. Wireless transmission is also very problematic, since video signals requires considerably wider bandwidth than underwater acoustic channels can provide. For example, the transmission of a monochrome TV quality video signal would require a compression rate in the order of 1250:1. Recent advances in signal and information processing technology have shown that the low-contrast and low-detailed nature of underwater imagery allows the utilization of massively compressing algorithms. A completely dark environment requires some lighting as well. The results indicate that good visual quality can be achieved by a very low-bit rate coding of an underwater video signal [Hoag et al., 1997]. An alternative solution for visual data extraction would be a *still-image camera* with a flashlight. Voice recording with a sensitive *microphone* is also possible along with on-line acoustic analysis methods, if enough DSP capacity is incorporated into the robot.

A *humidity sensor* or *condensation point sensor* mounted into the casing interior could be used for the robot's self-diagnostics to warn itself about leakage or condensation in the cover.

6.1.2 Actuators

The ability to agglomerate, i.e. form clusters, is a typical functional feature for living organisms. In the same biologically inspired way, the robots could agglomerate in order to focus and strengthen their collective effect, for example, while spreading some chemical substance.

Magnetic pads in the robot casing could be used to attach closely positioned robots together. If the magnetic force of a *permanent magnet* was weak enough, it would be easy for the robots to separate again just by changing their directions of motion to the opposite, i.e. one diving down, the other going upwards or maintaining the current depth. In the case of a stronger permanent magnet some mechanical solution should be used to disconnect the robots.

On/off control and a stronger contact force could be achieved by applying an *electrical magnet*. This kind of magnetic gripper could also allow the "anchoring" of the robots to metallic surfaces. However, a strong electrical magnet requires a relatively high current for the coil meaning considerable power loss. In addition, strong magnetic fields have a harmful effect on unshielded electronics, including the robot itself.

6.1.3 Communication methods

There are several applicable methods for wireless communication in a liquid environment: *ultrasonic-, infrared-, radio-, inductive-, and chemical communication.* The communication protocol for the SUBMAR society was developed as a higher level protocol for ASCII character transmission via serial port. Therefore, the same protocol could basically support other types of transmitters/receivers than the UHF radiomodule used.

1. *Ultrasonic communication* is definitely the most applicable for underwater communication purposes. Acoustic signals propagate well in conductive non-homogeneous liquids containing even considerable amounts of solid substance. Audibility depends strongly on the frequency used. In contrast to radio frequencies, no legislation exists for the use of acoustic frequency bands underwater. The complex problematics with acoustic underwater signals and data processing are related to multi-path propagation effects, damping, rough boundaries in sea surface/bottom, and inhomogeneities in the water volume caused by changes in temperature and pressure. These phenomena are thoroughly analyzed in [Hassab 1989].

In recent years, underwater acoustic communications technology has received a great deal of research attention. Efficient signal processing algorithms and modulation techniques have been introduced. Nowadays, for example, an acoustic communication system operating in the sea over several kilometers has a bandwidth in the order of 10 kHz, while a shorter range system operating over several dozens of meters may have a few hundred kHz available. The low frequency transducers designed for long-range communications are physically too large to be used in small-scale mobile applications. Nevertheless, recent advances in ultrasonic communication are encouraging for robotics applications [Stojanovic 1996], [Yuh 2000].

2. *Infrared light communication* can be applied only in clear liquids for a limited visible range, meaning that this method is useless in most real-world environments. With SUBMAR robots, infrared communication has been basically demonstrated within the emulated biomass system, presented in Section 5.1.2.

3. *Radio frequency communication* has been successfully used in SUBMAR robots for local short-range communication in the laboratory test environment. This was achieved in the electrically transparent plastic demo process filled with fresh water that was only somewhat conductive. Propagation of the RF signal in liquid media depends highly on the frequency used and the conductivity of the liquid. In more conductive liquids, like seawater, the RF signal will be completely blocked. Radically lower frequency than the UHF used would result wider range. An antenna could be integrated into the cover or left outside as a tail if longer antenna is required. But in any case, RF communication is far from the optimal solution in submerged applications.

4. *Inductive communication* is based on mutual inductance between two coils. This method was tested in the earlier SUBMAR prototype generations. The system is pictured in Figure 6.1. with the radio communication module. Since the communication range compared to energy consumption is relatively small for the inductive connection, a tag memory can be utilized as a temporary data storage to minimize energy consumption within the robot. The robot's own energy is consumed only while the contents of the onboard tag memory is read or written. The energy required for the actual transmission over a wider communication distance can be provided from the similar read/write -unit located outside the process, where a larger coil antenna can be wrapped around the pipe. Testing of the system proved that the inductive method is very difficult to apply to inter-robot communication, where a wider omnidirectional communication distance is required. However, as an operator interface for relatively narrow pipelines, the system seems to work well. Further details can be found in [Appelqvist 1996].

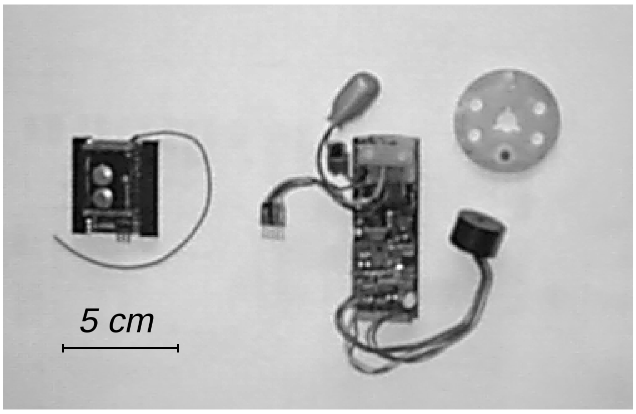


Figure 6.1 *Radiometrix BIM-433-F UHF-band radio communication module on the left; inductive communication system on the right consists of the Microlog read/write -unit, Antenna element 022, and an IDC 05008 Tag memory supplied by Idesco.*

5. *Chemical communication* through environment sensing is mentioned mainly as a theoretical possibility. Marker substances could be used to leave traces in the environment as signals. This function is partly demonstrated in Chapter 4, see Figure 4.5. Such primitive communication methods could be motivated only by strictly biomimetic research interests, emulating pheromones excreted by insects. In addition, signal detection with this method is obviously problematic, since markers dissolve and fade fast in liquid.

6.1.4 Positioning and navigation

The required accuracy and feasibility for a positioning system depend on the application. The robot's navigation strategy is closely related to the positioning task. Although motion control would remain underactuated, and navigation therefore partly stochastic, on-line *in situ* measurements and other actions benefit from accurate positioning. In the following, four different basic methods for positioning are discussed: *the feature-based approach, odometry, active beacons,* and *an inertial measurement system*.

Desired specifications for positioning accuracy are difficult to meet in a submerged environment, although, in unpressurized environments, the pressure value gives the Z-component (depth) explicitly. The best results can be achieved by creatively combining various methods and applying advanced statistical estimation methods, such as Kalman filtering, for data fusion from different sources when needed.

1. *Feature-based positioning* and navigation in its most minimalist form has been discussed in Chapter 4. Relying on the processing of the pressure sensor signal and its history information in a short time-window only, the method provides rough but robust *areal positioning for structured environments* having enough characteristic differences in depth. Additional sensors are required to bring horizontal positioning information.

The strength of the feature-based approach lies in the fact that additional information from different types of sources in various measures can be easily combined. For example, acceleration sensors reveal turbulent locations and collisions, while visual landmarks can be detected optically. In a process having long horizontal pipelines, the addition of the time dimension to measure times traveled for the links connecting the nodes can improve accuracy in mapping and navigation. Drawbacks are related to the constraints in accuracy set by the geometrical layout of the environment, especially in the XY-direction. Another limitation is that positioning and navigation require an initial *a priori* mapping process and structured operation environment on the whole.

2. *An odometry based positioning* method could be used to provide missing horizontal location information in certain environments. This requires that water-speed data and compass heading information are available. However, as in the case of SUBMAR, without any active horizontal propulsion a robot's true water-speed is difficult to sense and measure. In a restricted tank compartment this would require, for example, multi-directional sonar information. An omni-directional sonar would be a stand-alone positioning system itself.

3. *Active beacons* installed in the process can be used to create artificial landmarks for augmented feature-based positioning, or as a stand-alone 3D positioning system. In the latter case, in theory, at least three beacons should be installed into the space in a wide spatial configuration to guarantee unambiguous positioning. From a practical point of view, each compartment in the process volume requires its own beacons. Whether the distances from the beacons are detected as time of flight measurements or just based on the signal level analysis, it is, nevertheless, very challenging to realize an accurate 3D positioning system in a liquid environment. Beacons transmitting modulated acoustic ultrasonic signals would probably be the best solution for large compartments. Difficulties can be expected from echoing and multi-path transmission. Optical methods require clear liquids,

but signal fading still remains a major problem. Inductive beacons coiled around non-metallic pipes would be simple and cost-effective solutions to install complementary beacons for a pipeline network.

4. *Inertial positioning* can be basically utilized in the open and unstructured submerged environments in the same way as in airborne applications. Theoretical foundation and filtering techniques for advanced inertial navigation are well known and widely used (see for example, [Chatfield 1997]). The problems related to inertial positioning within the SUBMAR-type of robots has been discussed in Section 6.1.1. In outdoor underwater applications, the position correction from a GPS signal can be considered by coming up to the surface on a regular basis. In [Yun et al., 1999], such integrated GPS/inertial navigation systems assisted with water-speed sensor and compass is suggested for AUV navigation. The low cost and small size have been addressed in particular.

6.1.5 Motion and energy

V*ertical motion* can be achieved by varying the specific weight of the robot body compared to the surrounding liquid. In SUBMAR robots, multi-purpose inboard tank-actuators are used as diving tanks. To cope with greater alternations in the liquid density which can, for example, be caused simply by temperature variation, the capacity of the diving tank has to be relatively large compared to the total volume of the robot body. Alternative mechanisms are pictured in Figure 6.2.

By using the proposed mechanism based on axial movement between the casing halves, even a small axial adjustment will result in considerable change in the total volume because of the large cross-section area. Extensive reduction gearing is required for the motor shaft to provide enough torque for operation against outer pressure. A prototype of this construction was prepared and tested, shown in [Appelqvist et al., 1997], but water-resistant sealing and a rigid enough mechanical structure proved challenging to arrange with a very limited budget.

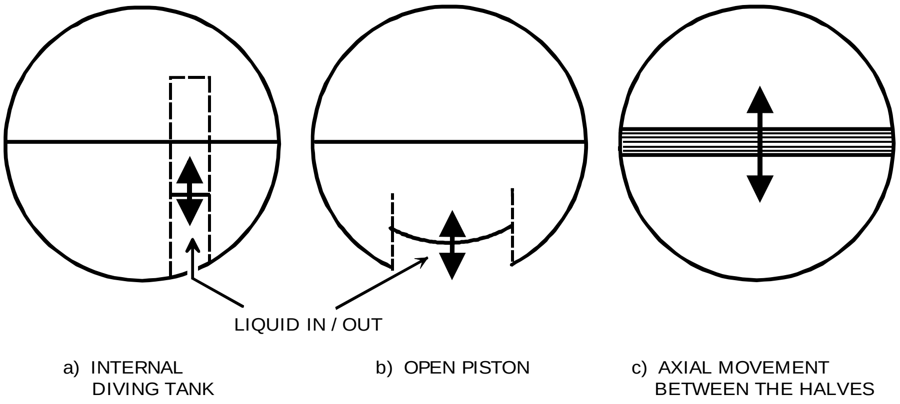


Figure 6.2 *Possible solutions to perform vertical movement.*

In some applications, the capability to perform active *horizontal motion* would be required. The desired motion may be more or less controlled. There are cases where any motion, even in random directions, can be highly useful. The idea is not to lose energy by trying to struggle against the process flow, but to provide a certain level of maneuverability to access locations where the liquid stands still, like in large tanks or reservoirs. It also serves as an emergency safety feature for the robot if it gets stuck somewhere.

Horizontal motion capability could be achieved, for instance, by installing propulsion tunnels through the casing. As an alternative motion mechanism for conventional propulsion, a flapping fishtail and/or fins could be added to the robot body. Fish swimming modes which generate robotic motion in an aquatic environment were studied in [Mason and Burdick 2000], while an example of a practical approach to robot swimming is presented in [Sfakiotakis et al., 1999]. At low speeds, these alternative thruster mechanisms are known to provide energy-efficient motion compared to propeller solutions. In [Arena et al., 1999], another biomimetic swimming mechanism, the undulatory-like motion of a sea-lamprey, has been studied for a robotic vehicle.

The capacity of stored energy will definitely remain the ultimate limitation in all mobile devices, including autonomous mobile robots. The level of energy consumption is closely related to the amount of motion characteristics needed; bare information processing, a sampling of sensors, and local communication is very energy efficient compared to motion generation. Therefore, passive motion is preferable. In an environment where the robots have access to a certain location(s) from time to time, the continuous autonomous functioning of the robots can be arranged by installing recharging stations in such locations. The design of a wireless recharging station supplying energy to the robots inductively inside the process has been suggested in [Appelqvist 1996]. Specific problems related to the autonomous recharging of NiMH-cells in mobile robots are well analyzed in [Birk 1997].

6.2 Potential applications

Having correct instrumentation on board, the SUBMAR type of sensor/actuator robots can be utilized in various real-world applications. The ability to acquire mobile on-line 3D measurement data from inside the process provides more accurate information than conventional fixed sensors. However, the idea is not to replace existing process instrumentation, but to provide a complementary source of information for automation systems controlling the processes. For instance, non-laminar flow profiles or concentration gradients could be analyzed with greater ease. Furthermore, certain on board actuators could be used for local control.

Potential applications can be found from the monitoring of flow-through processes in the petrochemical industry, pulp mills, water purifying plants, etc. High temperatures and other aggressive environmental conditions require innovative solutions and rugged materials. The validation and control of batch processes in food processing, fermentation, or the chemical and pharmaceutical industry could also be considered. For example, certain residual chemicals could be measured and watched over to indicate that the reaction has reached an end. Leakage detection and localization in long pipelines could be performed in the robots with spectral analysis based methods and sensitive on board microphones, as suggested in [Halme et al., 1997].

Environmental surveillance is discovered as another possible application domain for multiple small-sized mobile sensor/actuator platforms. The concept is wellsuited to pollution monitoring and water quality analysis in river and lake waterways. Various oceanographical studies, such as the mapping of sea currents are also possible. Nowadays, the GPS signal provides an excellent positioning reference for these outdoor applications while the robot is afloat.

6.3 Microengineering considerations

Although the existing size of the SUBMAR prototype robots (∅ ~11 cm) are already small enough for many useful applications, it is clear that the smaller size of the robot units would bring a completely new type of application to the scope. It can be estimated roughly, that with today's standard electronics assembly and component technology, by keeping the basic solutions, structure, and specifications of SUBMAR robots unaltered, it could be easily packed into the size of a tennis ball (∅ ~6.5 cm). With a considerably larger investment in the initial costs of production, and given that markets were open to a mass product, by applying ASIC technology and other customized solutions, the size of golf ball (∅ ~4.3 cm) would probably be a good target size for the robot.

However, to achieve something radically smaller, other technologies are required. MicroSystem Technology (MST) or MicroElectroMechanical Systems (MEMS) mean functional integration of mechanical, electronic, fluidic, optical, or any other elements by using special microengineering techniques to create highly integrated components or devices. Bulk and surface micromachining of silicon, LIGA, and laser micromachining techniques can be utilized to create 3D forms in silicon substrate. As a result of the research activity in the MST area, very small and accurate sensors, micro-actuators, as well as micro Total Analysis Systems (μTAS) have been manufactured. Concerning robotics applications, the most important achievements so far have been various mass produced sensors, for example, accelerometers and gyros for inertial navigation purposes. For further reading about MST and robotics, see [Fatikow and Rembold 1997] and [Will 2000].

A good example of an applicable μTAS component is a spectrometer manufactured by microParts, which is packed into an almost standard 24-pin DIP component package, making the whole package fit into a space smaller than 32x29x6 mm. With a custom package or installed as a bare chip, the size could even be radically smaller. In [Fukuda et al. 1995], a swimming microrobot platform is introduced. The motion mechanism is obtained by piezoactuator vibrated fins. The size of the platform is 34x19 mm.

By applying massive monolithic MST integration combining sensors, actuators, processor, supporting electronics, mechanics, etc., into a single chip, basically a true microrobot could be produced. Now, the targeted diameter for a robot could probably be in the order of a centimeter, depending of the functionalities. However, due to the different scaling of various forces in the micro domain, the operational principles of the robot would need complete reconsideration and redesign. The cost of a monolithic integration process is tremendously high, meaning that a production series should be extremely large. Although there are no theoretical restraints for a monolithic integration, a hybrid, modular, component-based MST integration is a more realistic approach with the existing technology.

Chapter 7

Conclusions

7.1 Summary and conclusions

In this thesis, the achievements from systems level design leading to mechatronics design, implementation, and the testing of a Robot Society system have been presented in the form of a case study. Naturally, the setup of only one particular system has been analyzed, while each application and installation will require specific solutions. However, on a more general level the basic problems and potential are common to all autonomous mobile multi-robot systems. It has to be noted also, that the starting point for the design process of the whole system has been strongly research oriented, rather than any specifically targeted application. Therefore, a classical engineering design process with accurate definition of technical specifications and user requirements at the beginning of the project have been impossible. Although the original targets and tasks have changed slightly during the process, the ultimate goal and aims for the study have been clearly reached.

Research work with SUBMAR robots verified that even from very minimalist robot units it is possible to build up an effective system capable of coping autonomously with relatively complex tasks. Minimalism is often thought to be attractive from the engineering point of view. The fewer the parts, the fewer the potential problems. In many cases, this applies both to mechanical and electrical hardware, while for software the situation is not so straightforward. The length of a program code cannot be used to estimate the reliability of the software. Besides that watertight testing of complex embedded software systems has proven virtually impossible, potential emergent features due to reactive software components increase the risk of unwanted effects in functioning. Therefore, the safety aspects of an autonomously functioning robotic system have to obtain a very high prioritization in the design process.

The testing of the SUBMAR society was affected by limitations and difficulties with the sensing of the emulated biomass growth. Actually, the emulated biomass system became a very realistic case partly by mistake; it would have been possible to ensure correct measurement values for the robots just by applying modulated coding for the emitted IR signals. The resulting erroneous robot consciousness degraded the performance of the control architecture. The benefits of inter-robot communication and the functioning of self-optimizing features were disturbed quite significantly. Nevertheless, despite perception problems, the robots managed to accomplish their tasks successfully, which proved obvious system robustness. These lessons provided a well-grounded reminder of the problems related to 3D distributed measurements encountered by robots in real-world situations.

The communication system itself seemed to perform well. Even with the most efficient communication protocol, nevertheless, it is evident that some part of the information will be lost in a spatially decentralized system. However, if the communication structure is well designed, some loss of information will not harm the functioning of the society. In the worst case, some actions will just be delayed.

As a result of continuous research work and systems development for five years and three prototype generations, profound knowledge has been gained and new solutions presented as the required technology for minimalist mobile robots operating in liquid process environments. The SUBMAR Robot Society, shown in Figure 7.1, forms a technological basis for the development of real-world applications which may combine robotics and process automation systems in a novel way in the future.

Figure 7.1 *SUBMAR Robot Society on standby for a new mission…*

7.2 Future work

Concerning mobile robotics research in general, sheer computational capacity for embedded processing seems to have reached a sufficient level for quite a variety of tasks. Instead, a great deal of unused potential can be found from a more efficient processing of the acquired sensor information and sensor development itself. This applies to SUBMAR robots as well.

In the future, attention will be paid to the quality of perception to enhance robot consciousness and thereby the performance of the whole system. More advanced processing of the measurement information from various sources, along with more accurate positioning information will be the main objectives for further development of the SUBMAR society. Furthermore, the development of a user interface for the Robot Society is important. It should allow the robots' connection to automated process control systems as a standard instrumentation and support 3D visualization of the collectively acquired information. Another interesting challenge requiring further effort would be the more theoretical formulation of the Robot Society control architecture and statistical modeling of the functioning of the system.

To conclude, research work with the SUBMAR society will continue in a more application-oriented direction. In the near future, the feasibility of an application to environmental monitoring and surveillance in the sea environment will be carefully explored.

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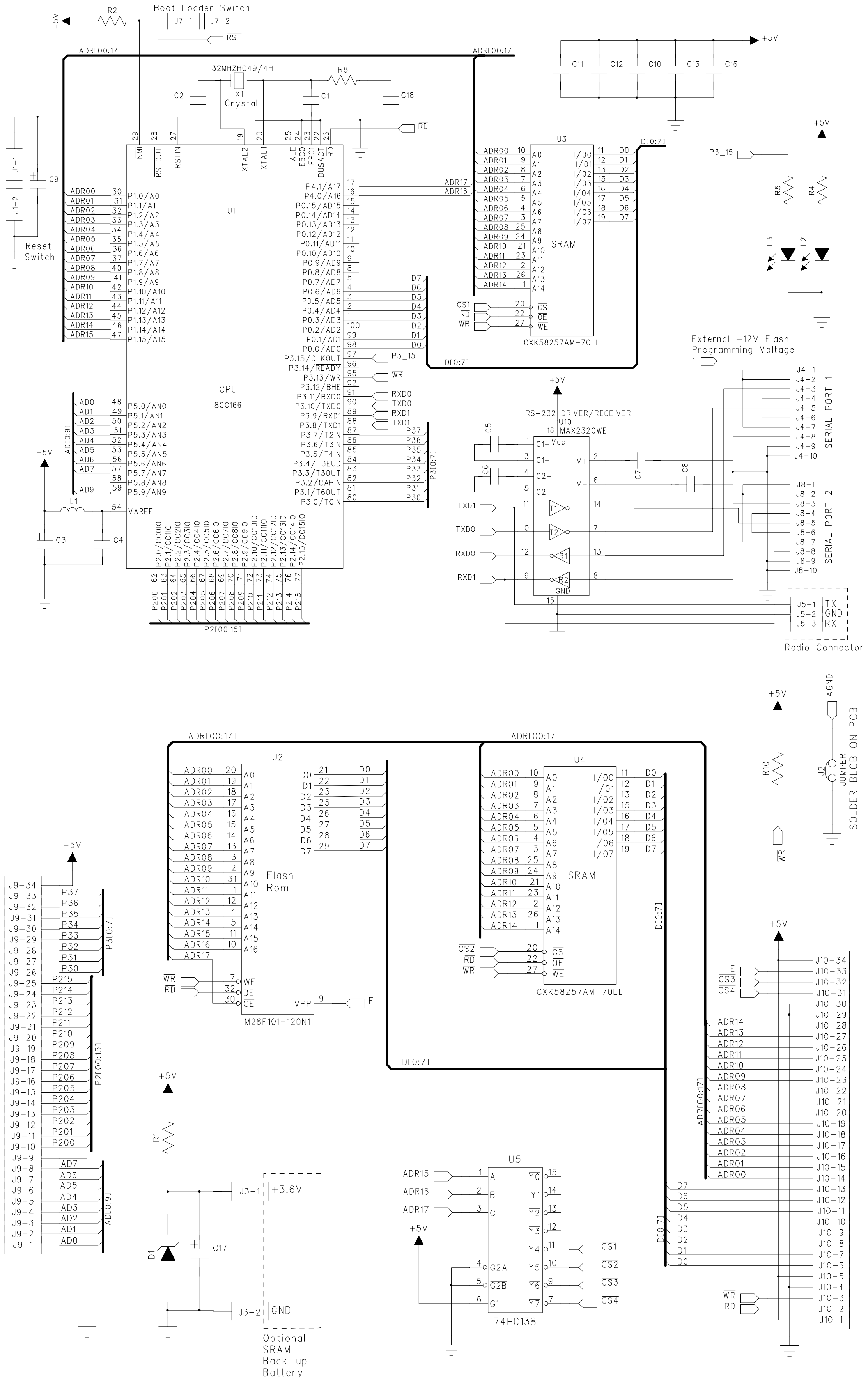
Appendices

Appendix A Schematic layout of SUBMAR CPU module
Appendix B Schematic layout of SUBMAR Power module
Appendix C Schematic layout of SUBMAR Amplifier module
Appendix D Schematic layout of SUBMAR Motor control module
Appendix E Schematic layout of SUBMAR Communication module
Appendix F Schematic layout of SUBMAR Infrared module

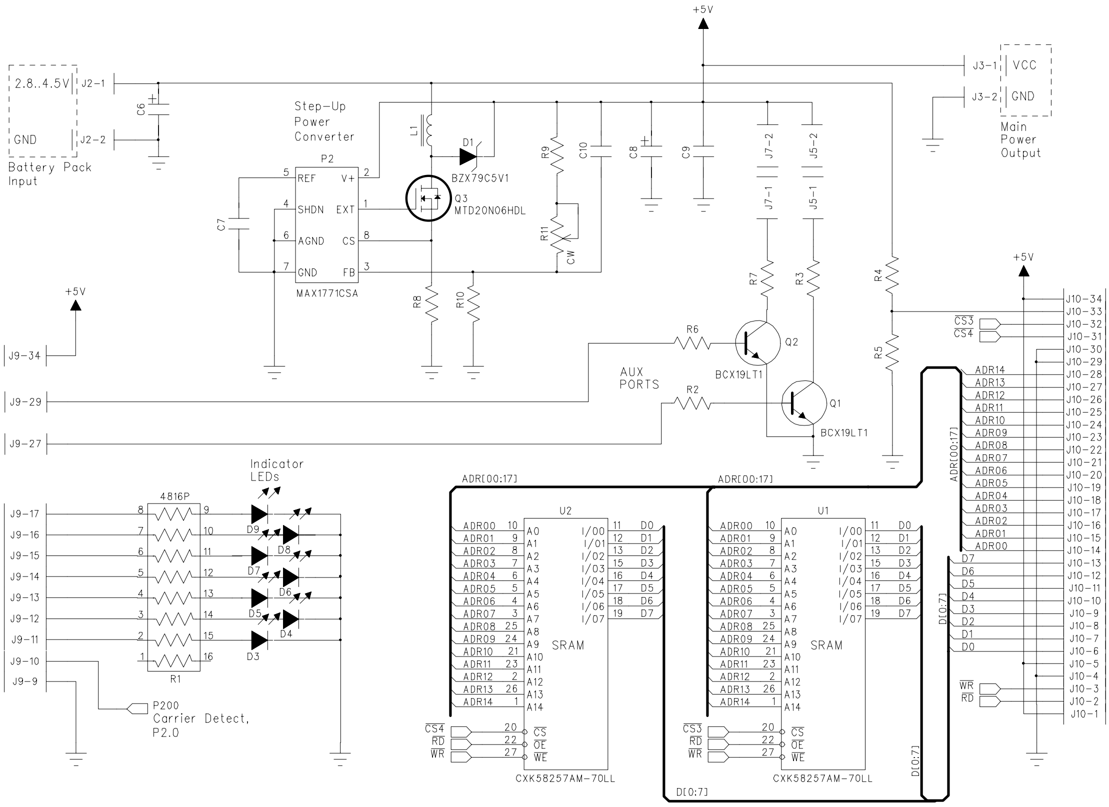
Appendix G Tests from Experiment Series I (1 robot)
Appendix H Tests from Experiment Series I (3 robots, no IRC)
Appendix I Tests from Experiment Series I (3 robots, C-type IRC)
Appendix J Tests from Experiment Series I (5 robots, no IRC)
Appendix K Tests from Experiment Series I (5 robots, C-type IRC)
Appendix L Tests from Experiment Series I (5 robots, CC-type IRC)

Appendix M Tests from Experiment Series II (3 robots, no IRC)
Appendix N Tests from Experiment Series II (3 robots, IRC)
Appendix O Tests from Experiment Series II (5 robots, no IRC)
Appendix P Tests from Experiment Series II (5 robots, IRC)

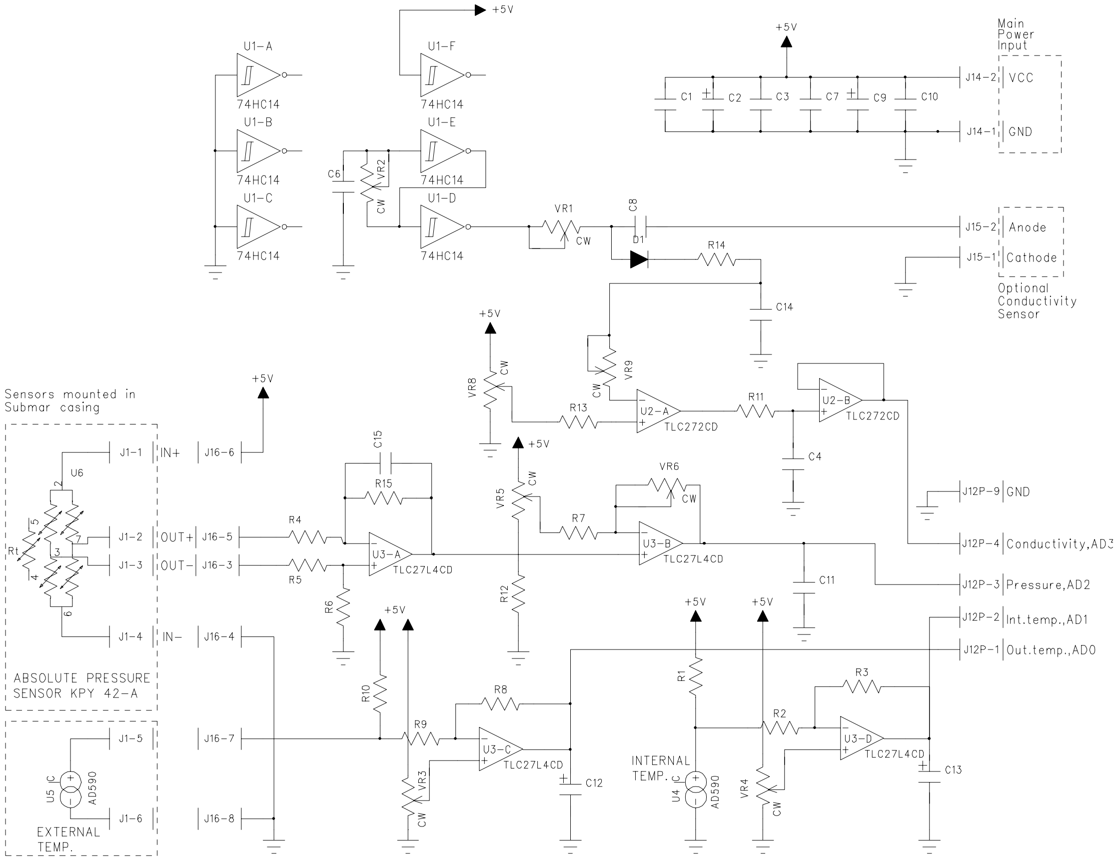
Appendix A Schematic layout of SUBMAR CPU module



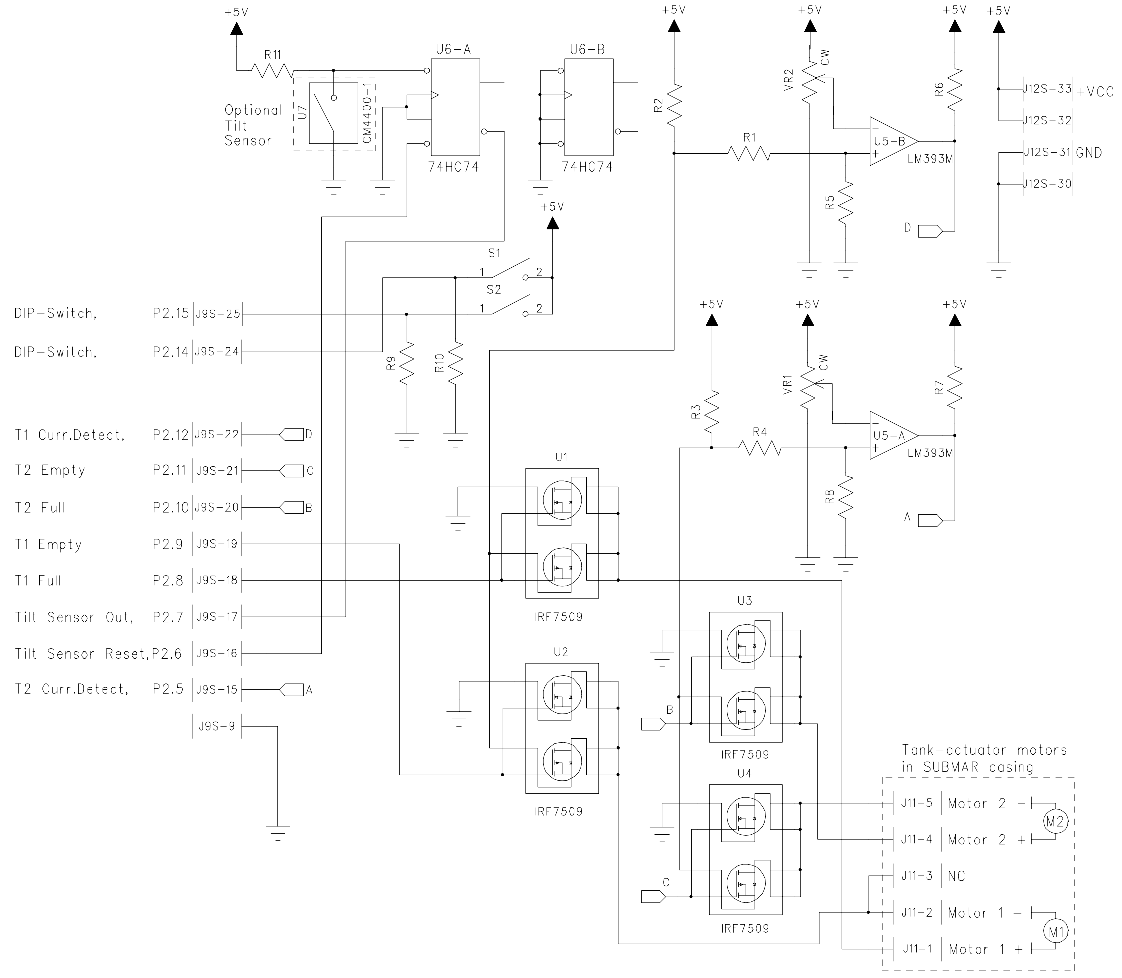
Appendix B Schematic layout of SUBMAR Power module



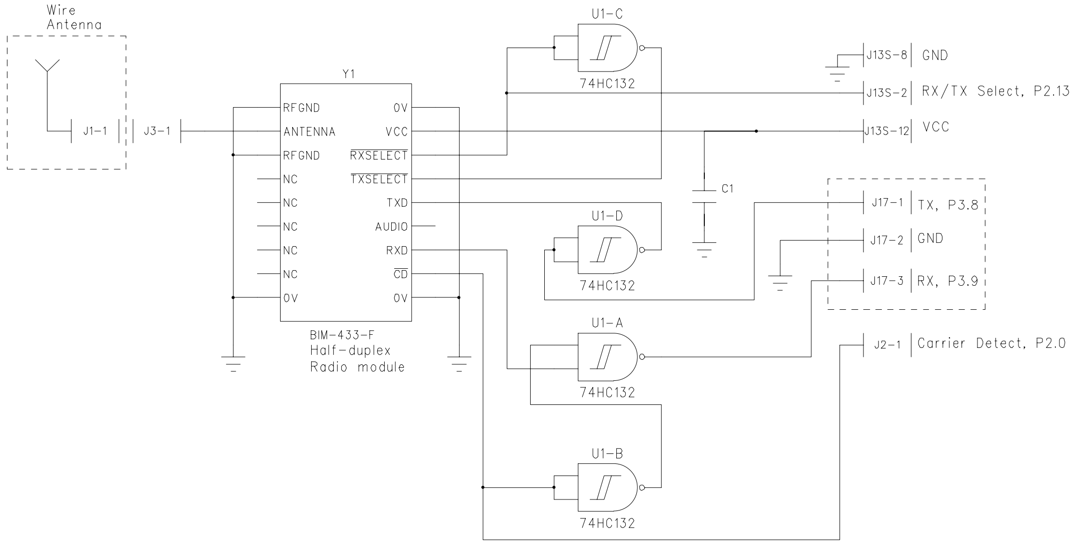
Appendix C Schematic layout of SUBMAR Amplifier module



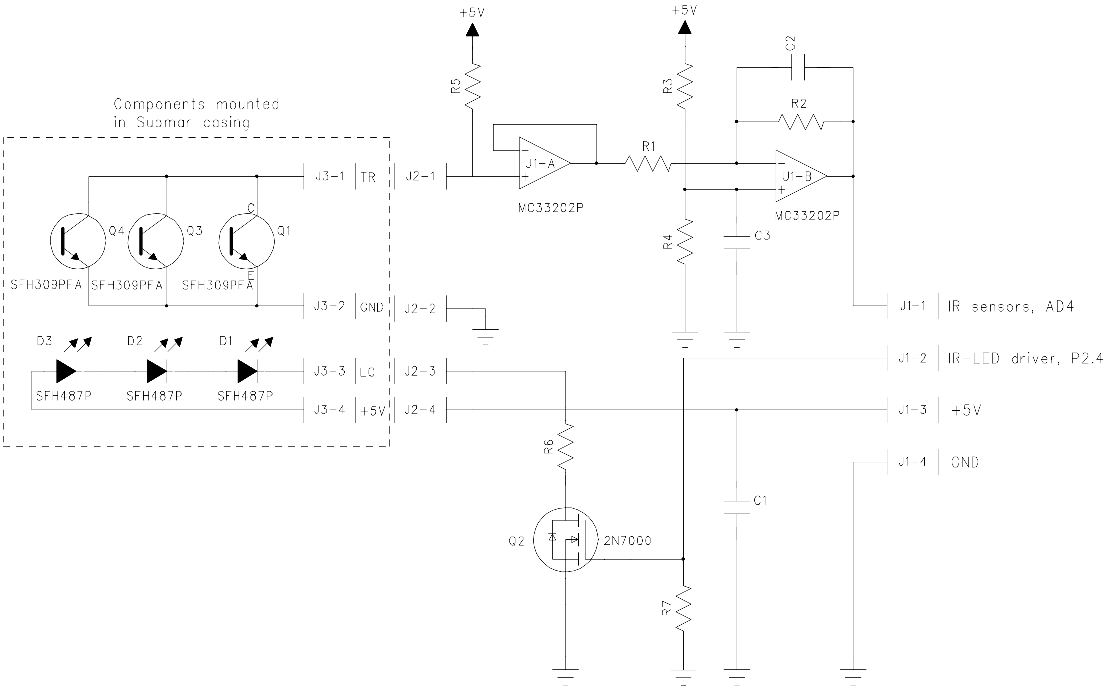
Appendix D Schematic layout of SUBMAR Motor control module



Appendix E Schematic layout of SUBMAR Communication module



Appendix F Schematic layout of SUBMAR Infrared module

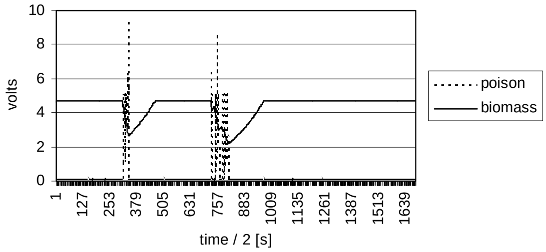


Appendix G

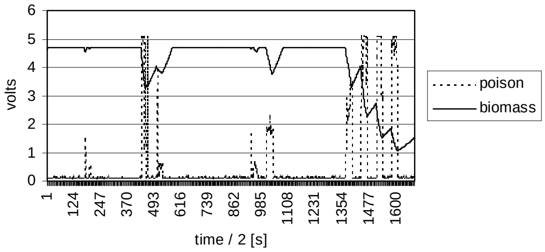
Tests from Experiment Series I (1 robot)

1/2

1 robot, 1/0807, growth 1



1 robot, 1/0807, growth 2



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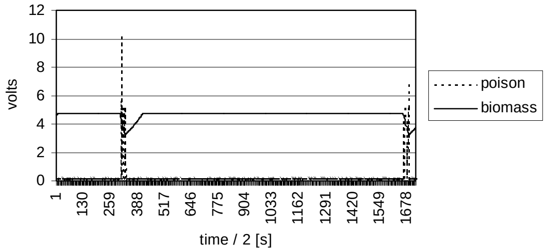

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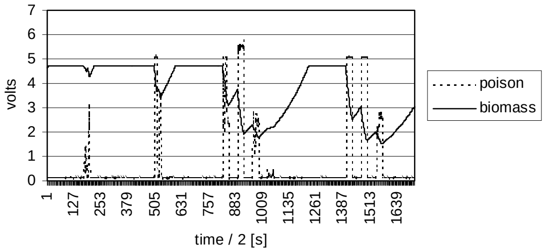

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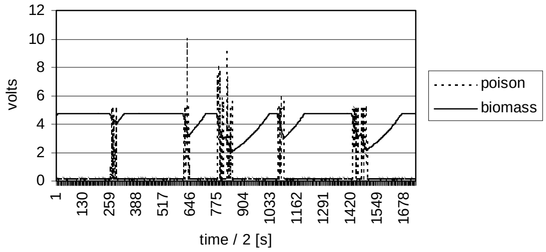

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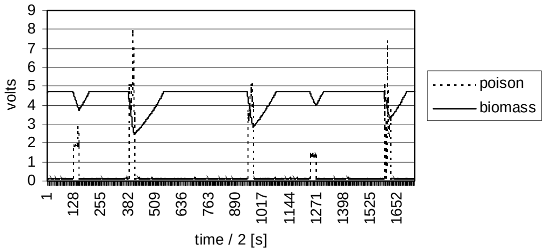
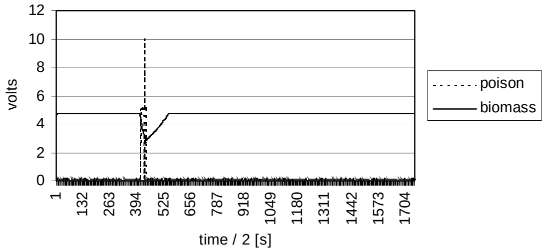


1 robot, 4/0807, growth 1



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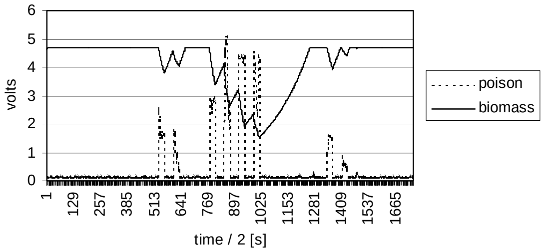
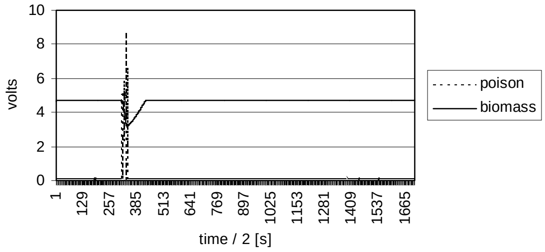
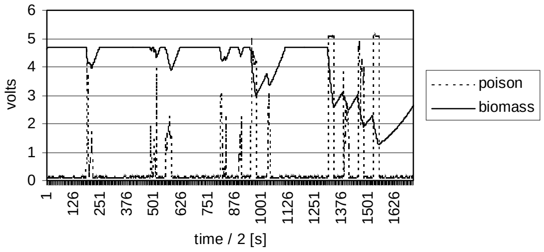


1 robot, 5/0807, growth 1



1 robot, 5/0807, growth 2



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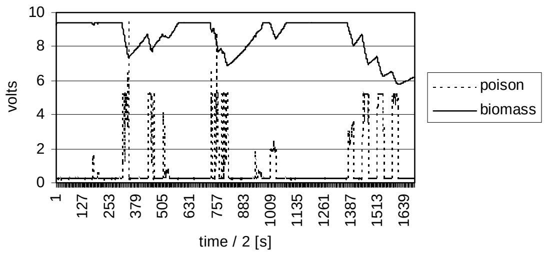

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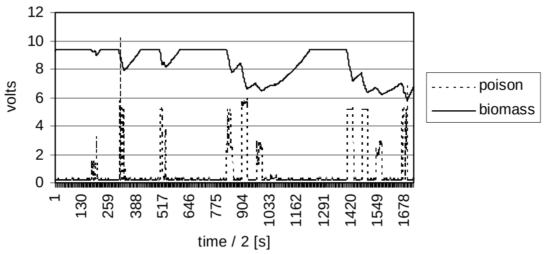
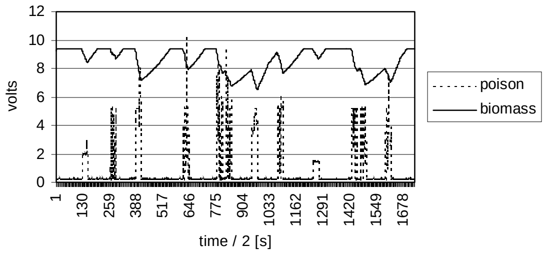


1 robot, 3/0807, total



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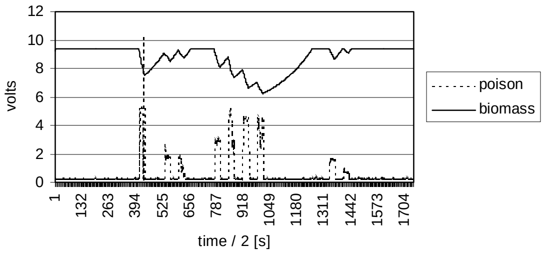
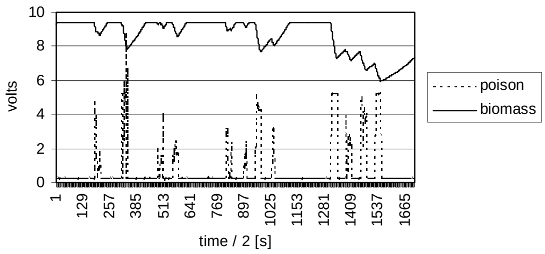
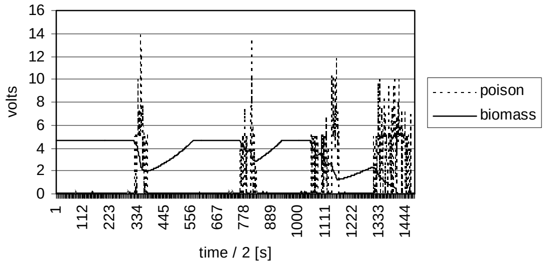


1 robot, 5/0807, total



Appendix H Tests from Experiment Series I (3 robots, no IRC) 1/3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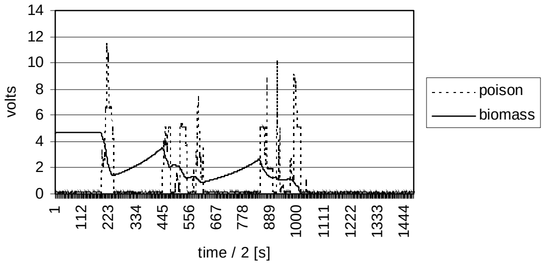
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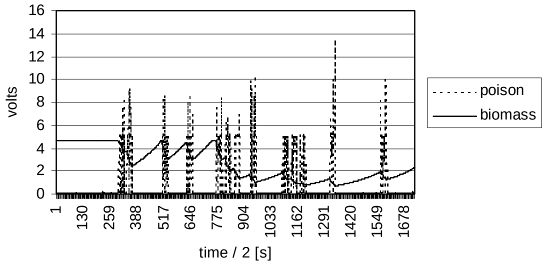
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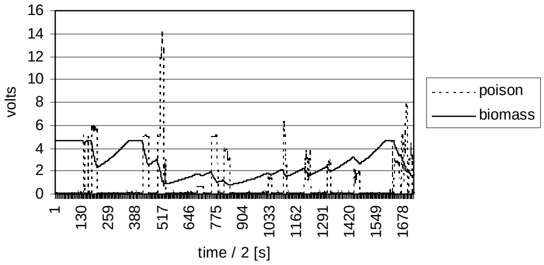
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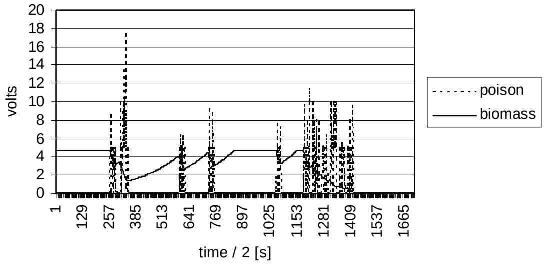
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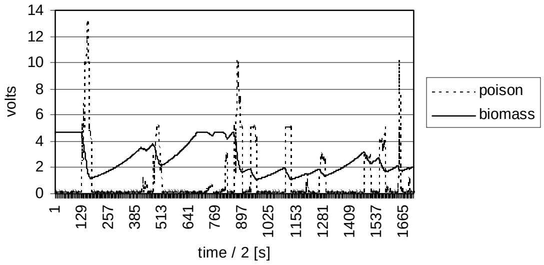
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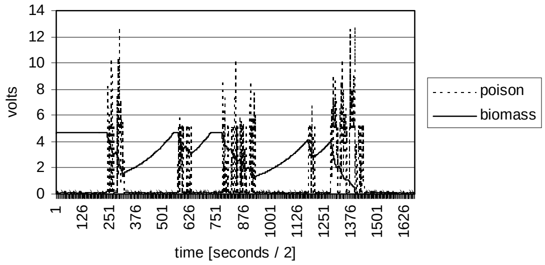
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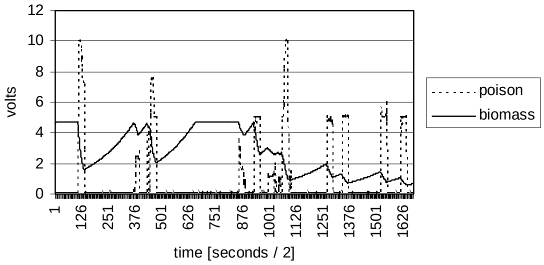
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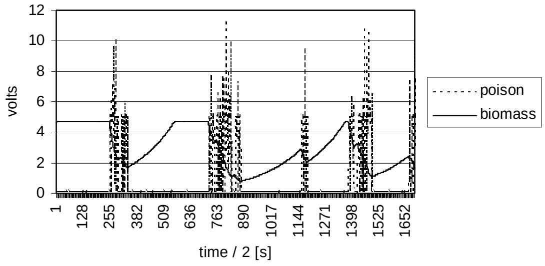
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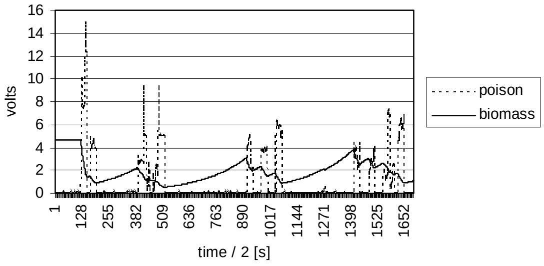
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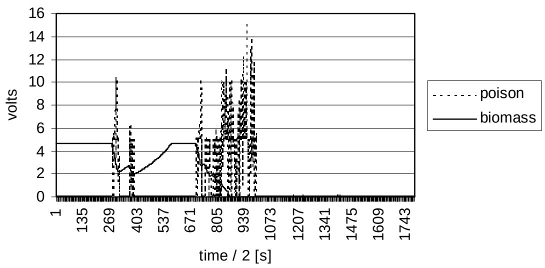
3 robots (NC), 6/0507, growth 1



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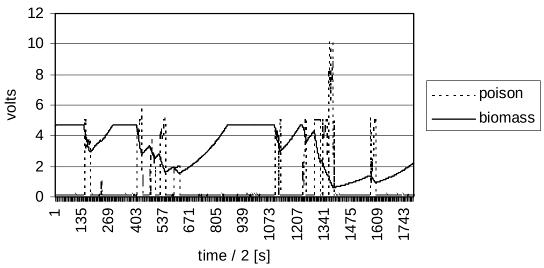

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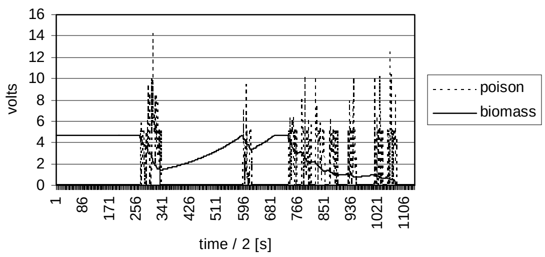
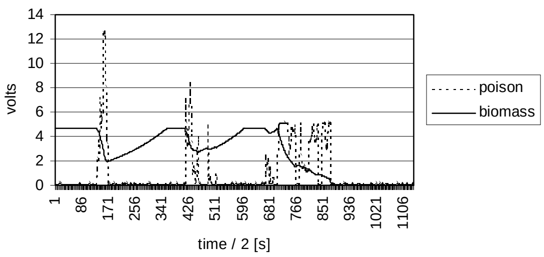
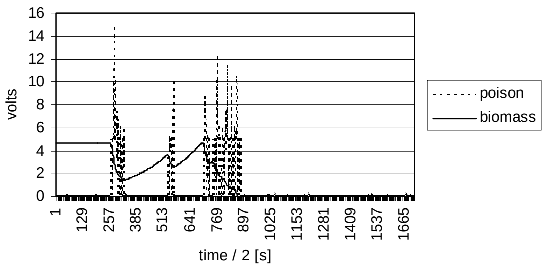


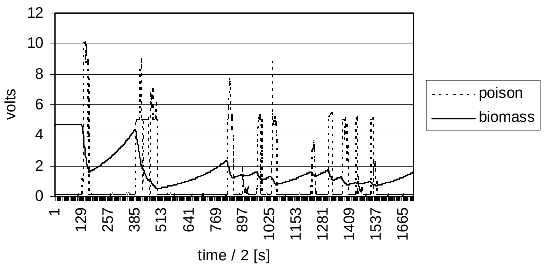
3 robots (NC), 7/0607 , growth 2



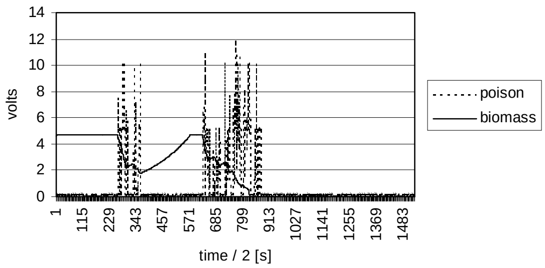
3 robots (NC), 8/0507, growth 1



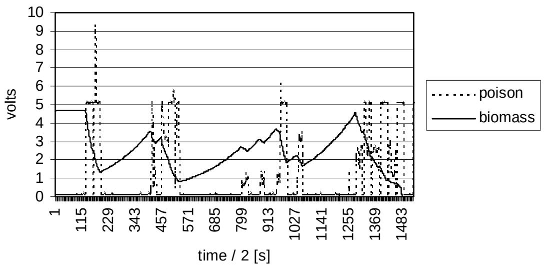
3 robots (NC), 8/0507, growth 2



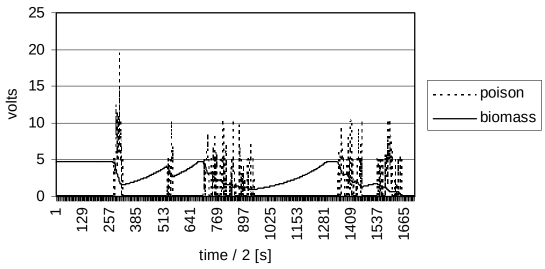
3 robots (NC), 9/0507, growth 1



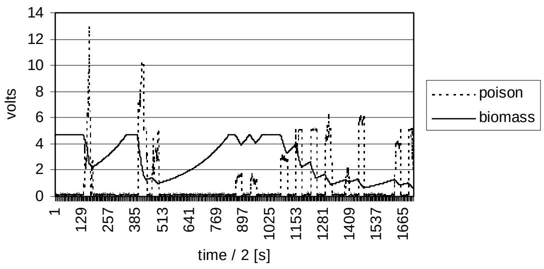
3 robots (NC), 9/0507, growth 2



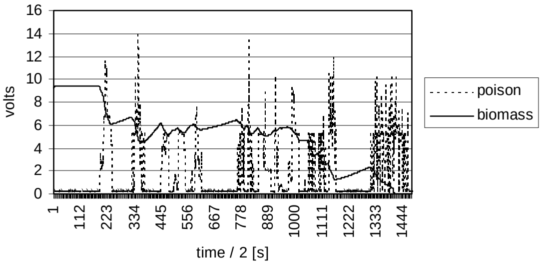
3 robots (NC), 10/0507, growth 1



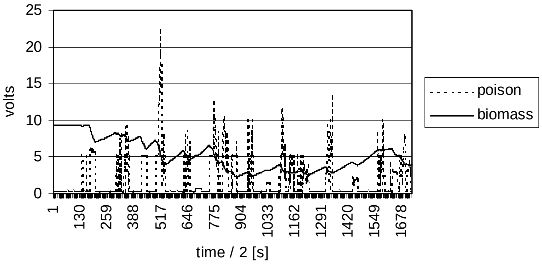
3 robots (NC), 10/0507, growth 2



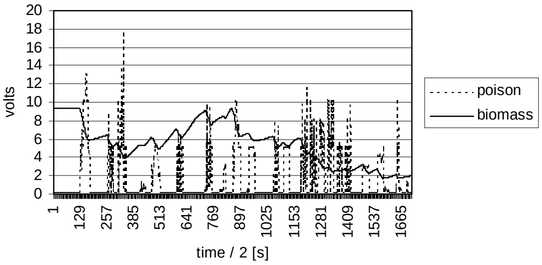
3 robots (NC), 1/0207, total



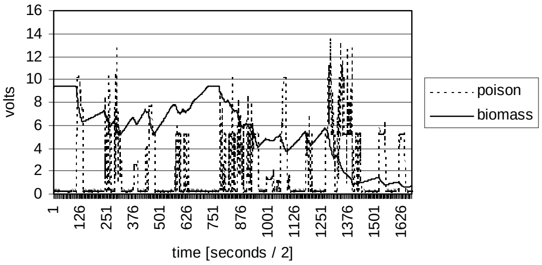
3 robots (NC), 2/0207, total



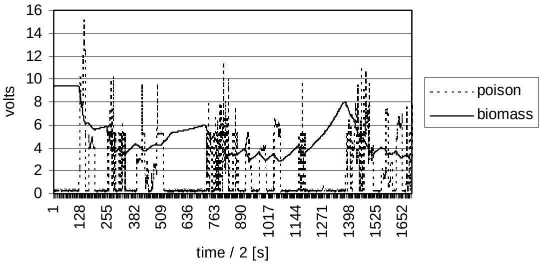
3 robots (NC), 3/0207, total



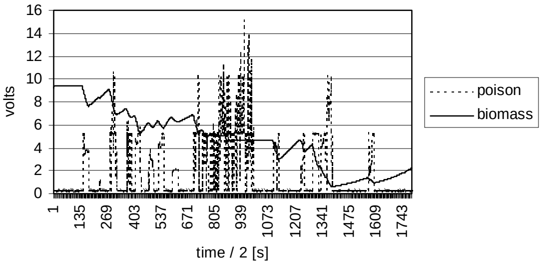
3 robots (NC), 4/0407, total



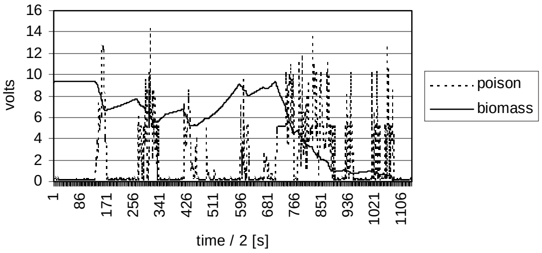
3 robots (NC), 5/0407, total



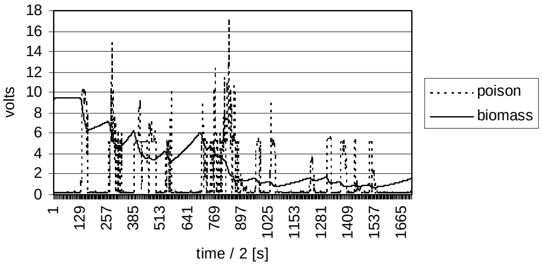
3 robots (NC), 6/0507, total



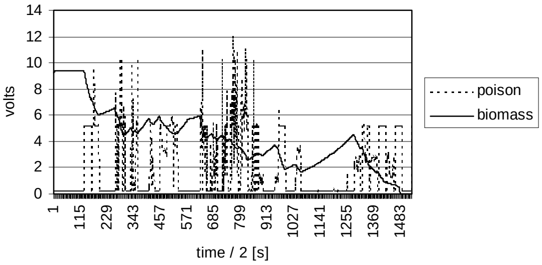
3 robots (NC), 7/0607 , total



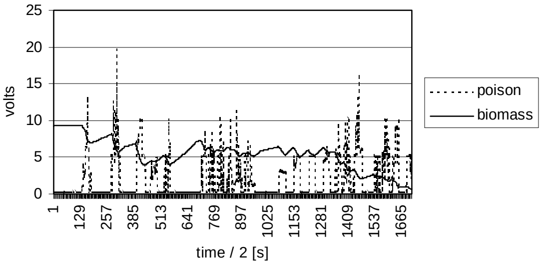
3 robots (NC), 8/0507, total



3 robots (NC), 9/0507, total

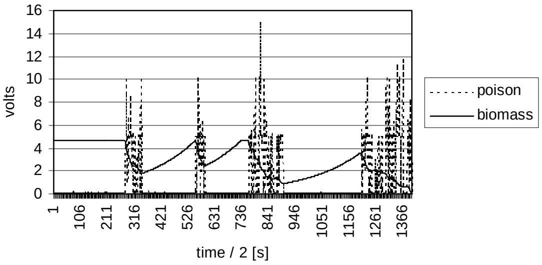


3 robots (NC), 10/0507, total

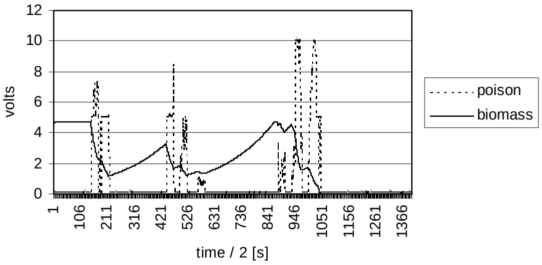


Appendix I Tests from Experiment Series I (3 robots, C-type IRC) 1/3

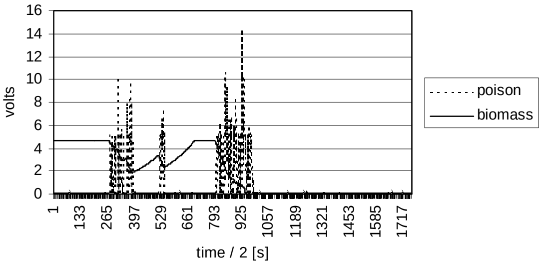
3 robots (C), 1/0107, growth 1



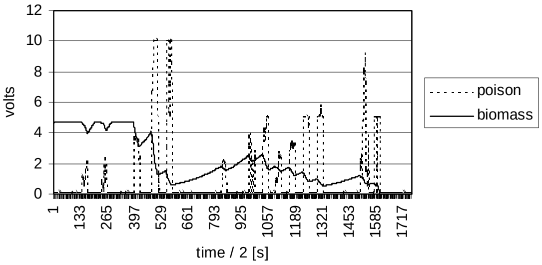
3 robots (C), 1/0107, growth 2



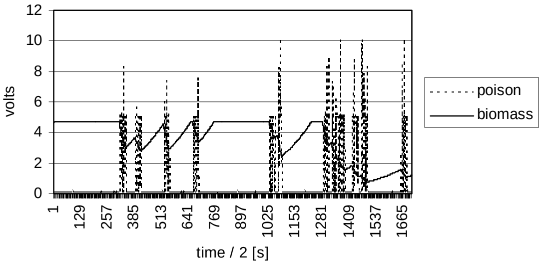
3 robots (C), 2/0107, growth 1



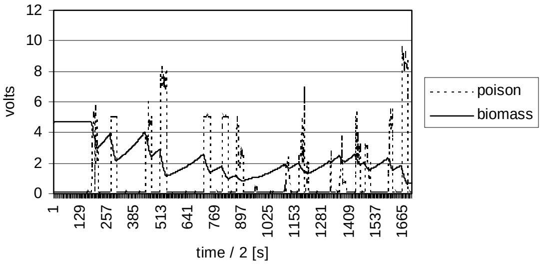
3 robots (C), 2/0107, growth 2



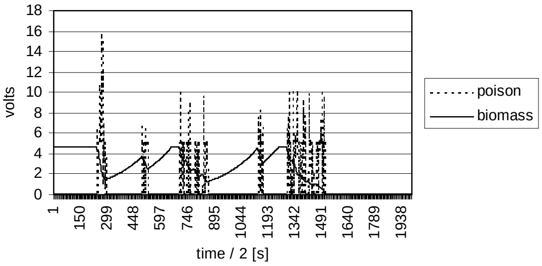
3 robots (C), 3/0107, growth 1



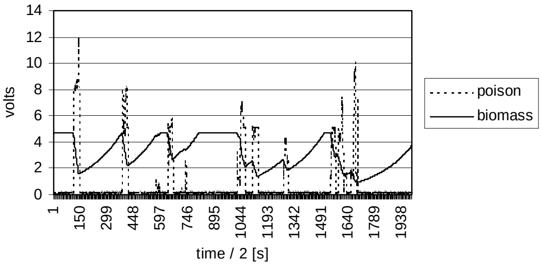
3 robots (C), 3/0107, growth 2



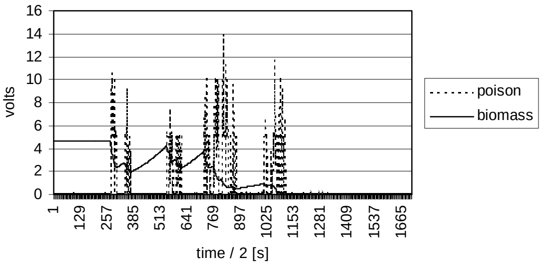
3 robots (C), 4/02.07, growth 1



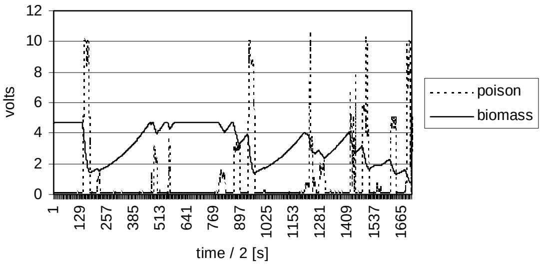
3 robots (C), 4/02.07, growth 2



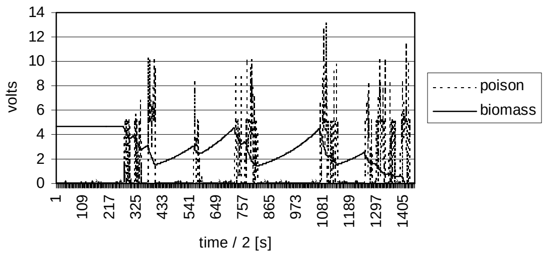
3 robots (C), 5/0207, growth 1



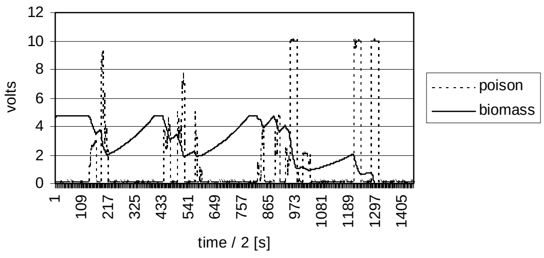
3 robots (C), 5/0207, growth 2



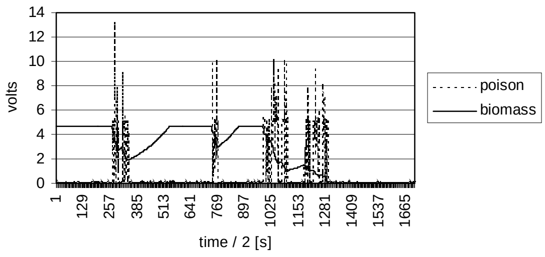
3 robots (C), 6/0607, growth 1



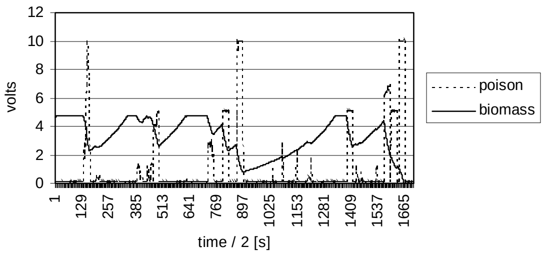
3 robots (C), 6/0607, growth 2



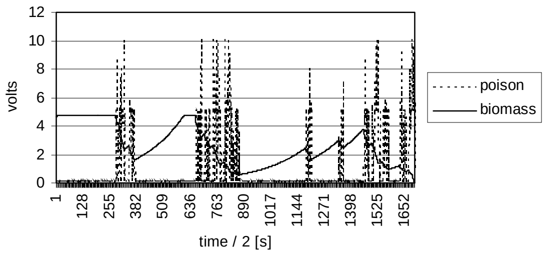
3 robots(C), 7/0607, growth 1



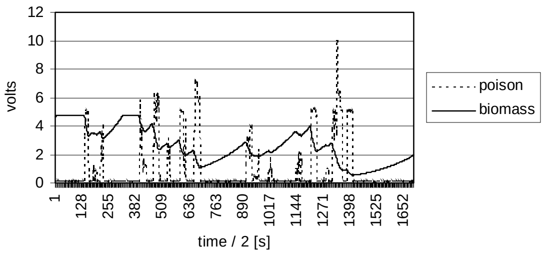
3 robots(C), 7/0607, growth 2



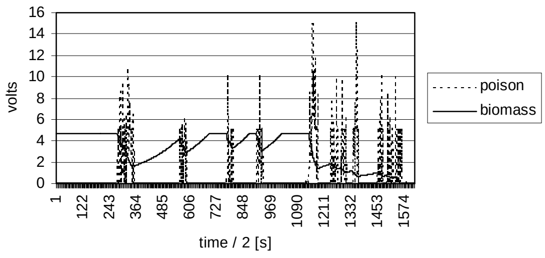
3 robots (C), 8/0607, growth 1



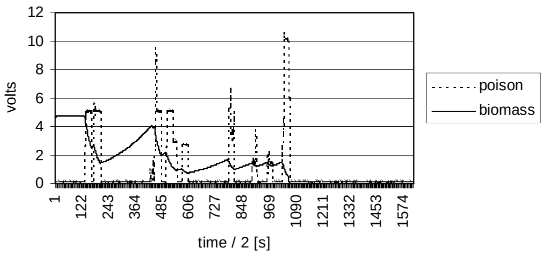
3 robots (C), 8/0607, growth 2



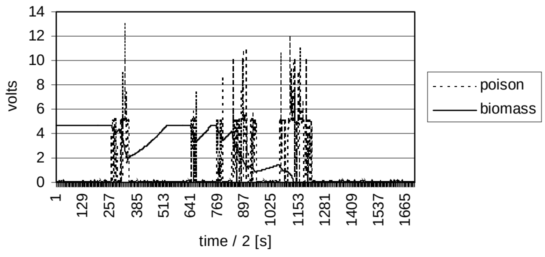
3 robots (C), 9/0607, growth 1



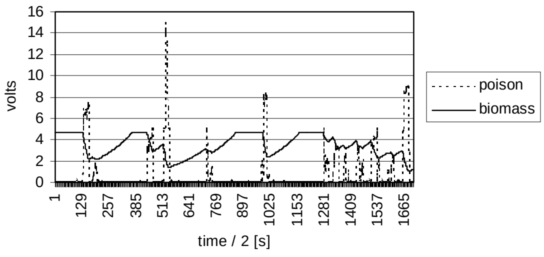
3 robots (C), 9/0607, growth 2



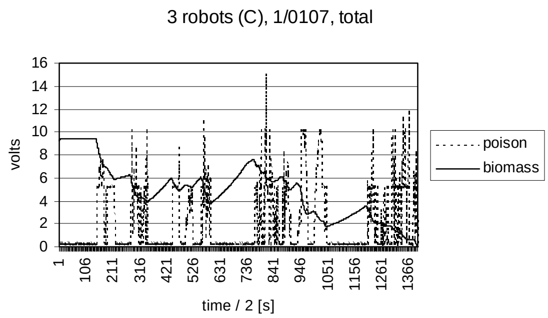
3 robots (C), 10/0607, growth 1

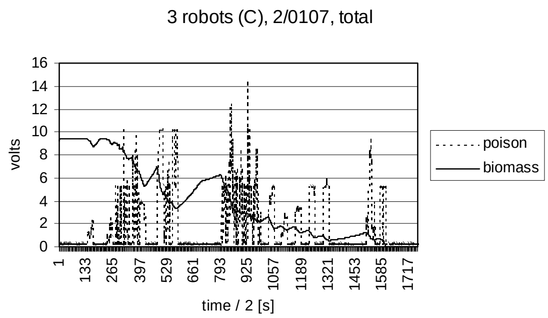


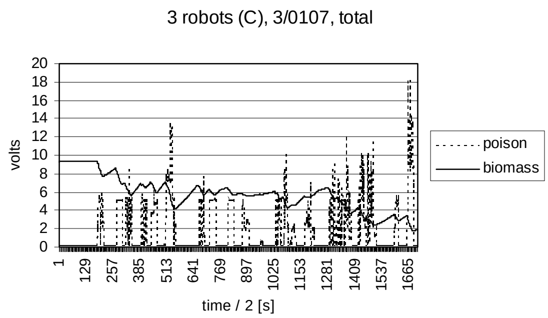
3 robots (C), 10/0607, growth 2

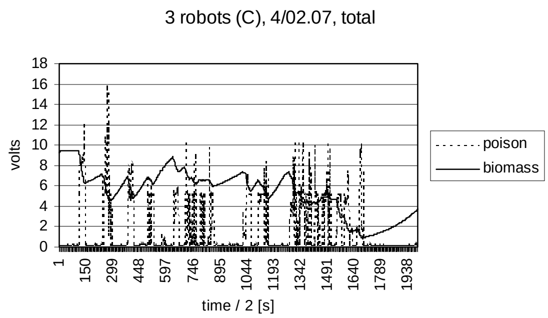


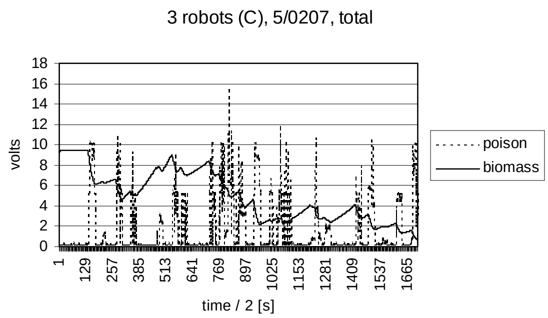
Appendix I Tests from Experiment Series I (3 robots, C-type IRC) 3/3

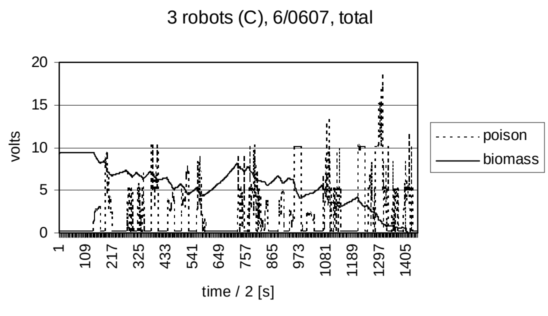


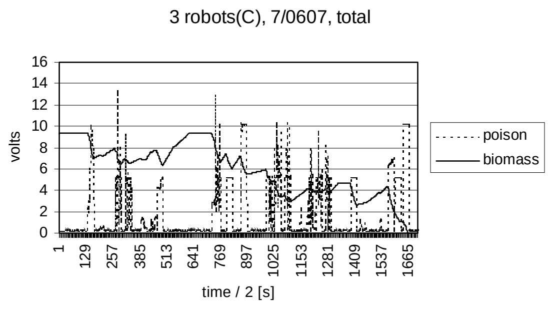


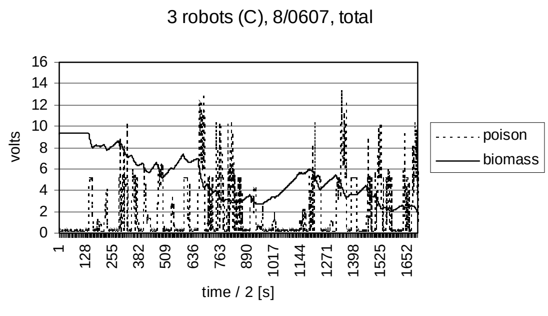


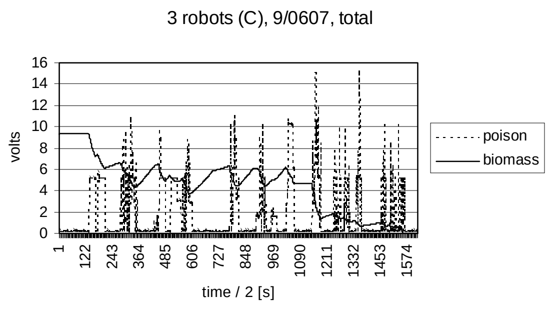


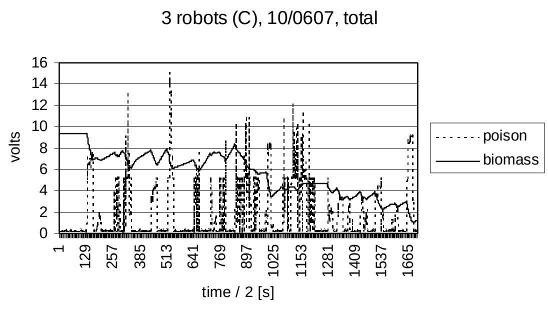






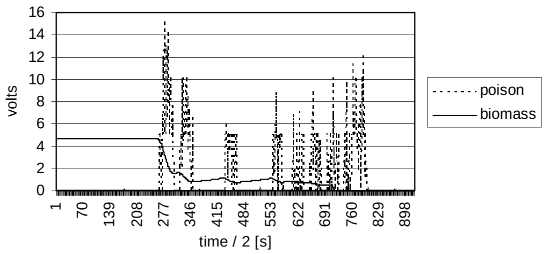




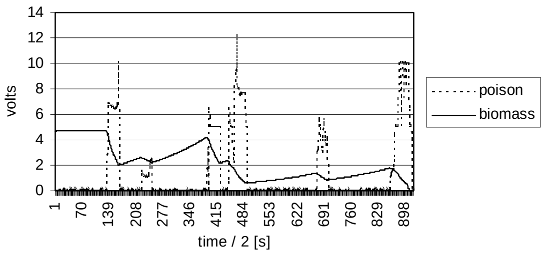


Appendix J Tests from Experiment Series I (5 robots, no IRC)

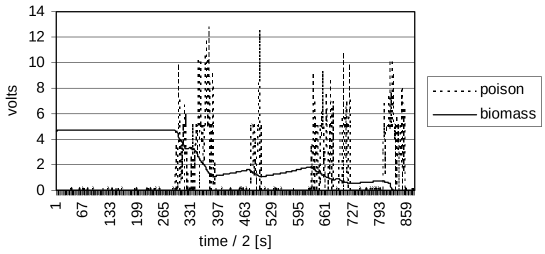
5 robots (NC), 1/1307, growth 1



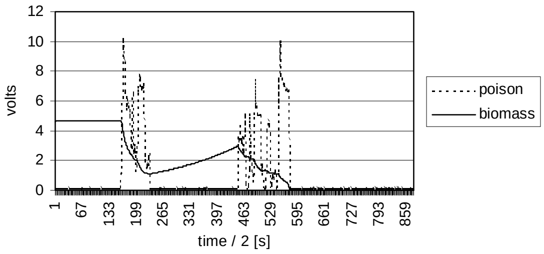
5 robots (NC), 1/1307, growth 2



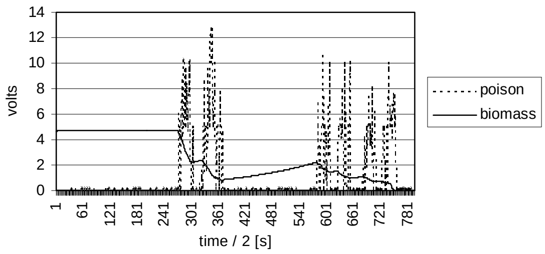
5 robots (NC), 2/1307, growth 1



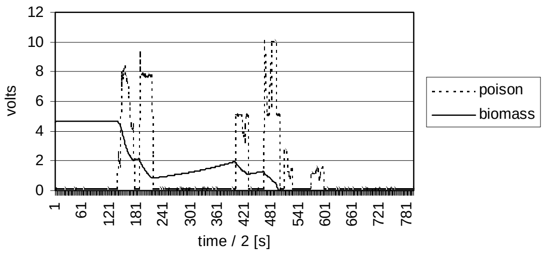
5 robots (NC), 2/1307, growth 2



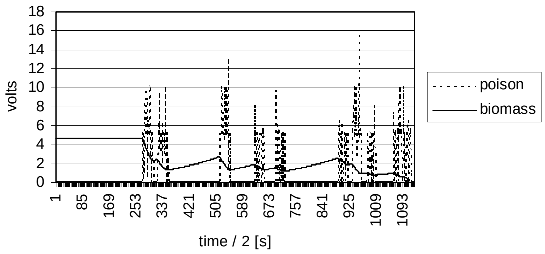
5 robots (NC), 3/1307, growth 1



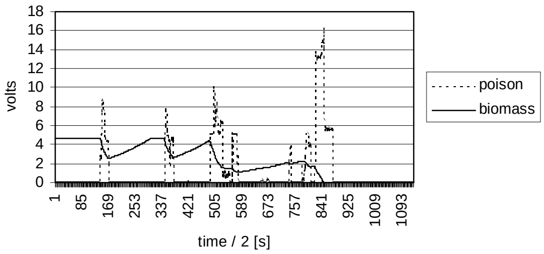
5 robots (NC), 3/1307, growth 2



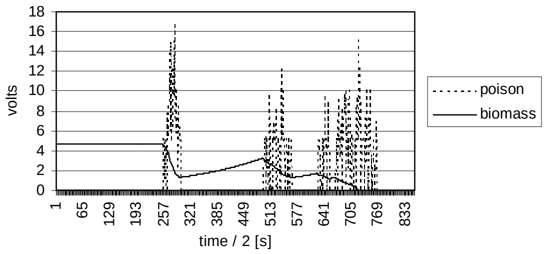
5 robots (NC), 4/1307, growth 1



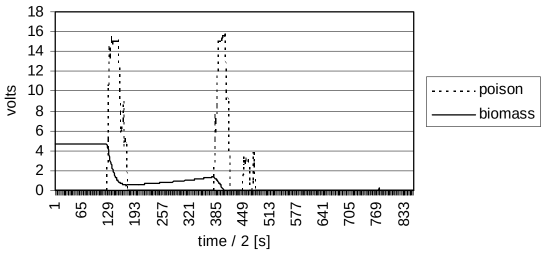
5 robots (NC), 4/1307, growth 2



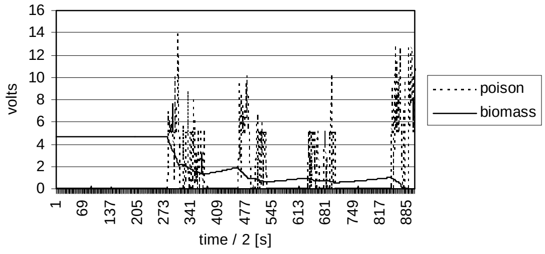
5 robots (NC), 5/1407, growth 1



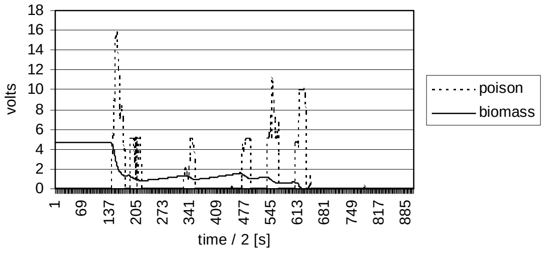
5 robots (NC), 5/1407, growth 2



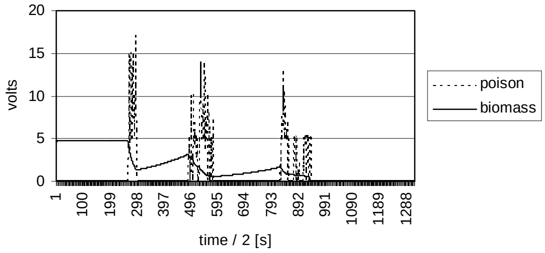
5 robots (NC), 6/1407, growth 1



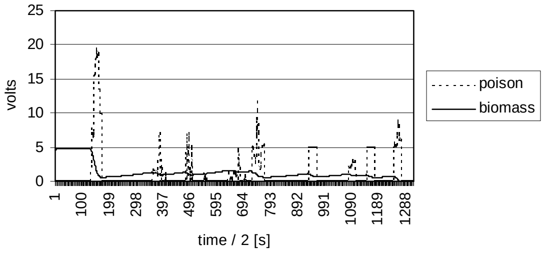
5 robots (NC), 6/1407, growth 2



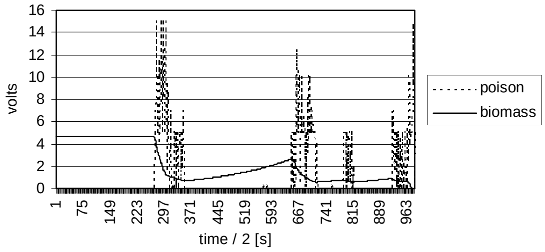
5 robots (NC), 7/1407, growth 1



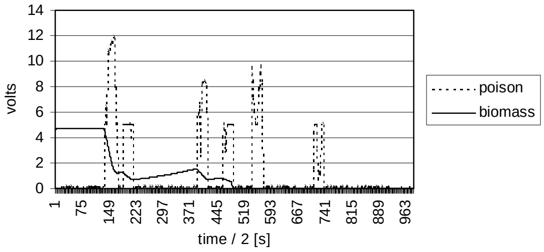
5 robots (NC), 7/1407, growth 2



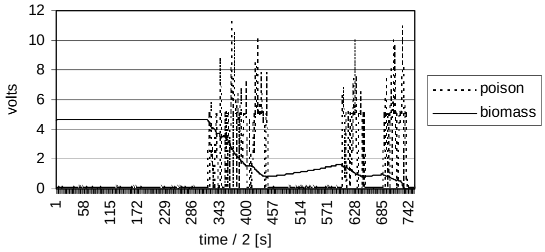
5 robots (NC), 8/1407, growth 1



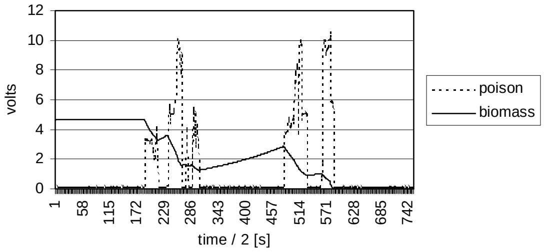
5 robots (NC), 8/1407, growth 2



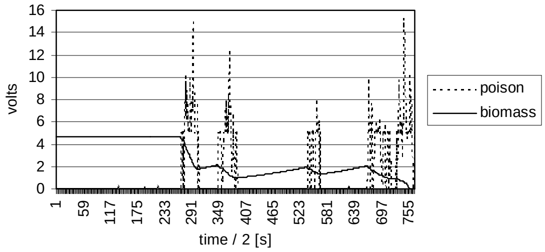
5 robots (NC), 9/1407, growth 1



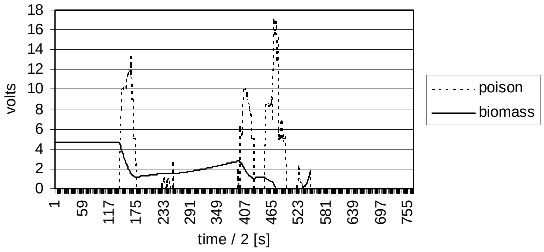
5 robots (NC), 9/1407, growth 2

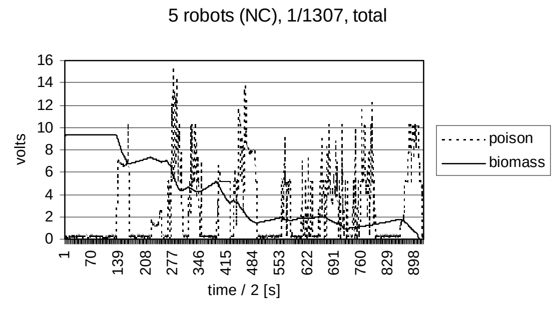


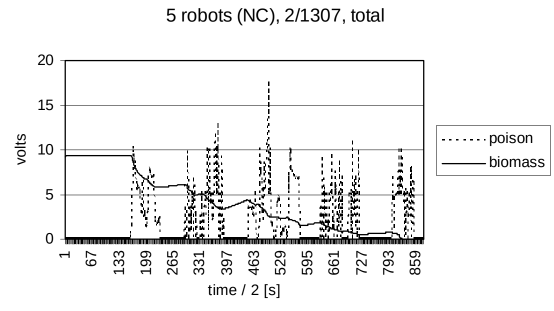
5 robots (NC), 10/1407, growth 1

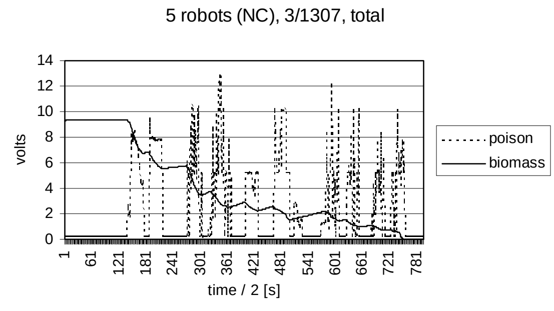


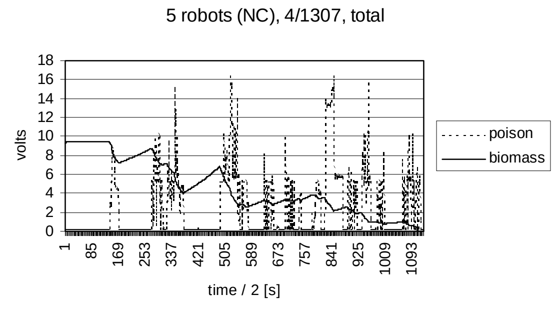
5 robots (NC), 10/1407, growth 2

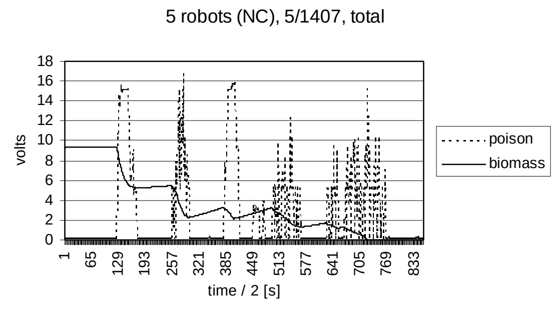


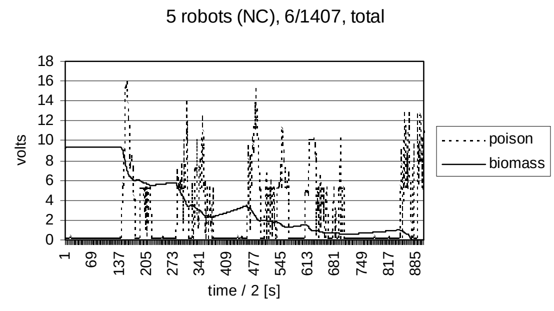

5 robots (NC), 1/1307, total
volts
16
14
12
10
8
6
4
2
0
1
70
139
208
277
346
415
484
553
622
691
760
829
898
time / 2 [s]
poison
biomass

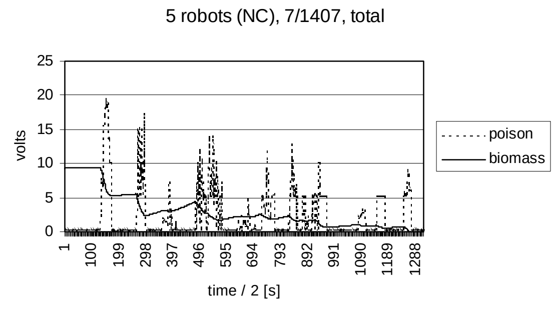

5 robots (NC), 2/1307, total
volts
20
15
10
5
0
1
67
133
199
265
331
397
463
529
595
661
727
793
859
time / 2 [s]
poison
biomass

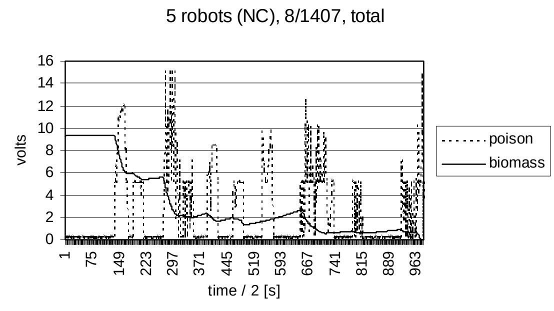

5 robots (NC), 3/1307, total
volts
14
12
10
8
6
4
2
0
1
61
121
181
241
301
361
421
481
541
601
661
721
781
time / 2 [s]
poison
biomass

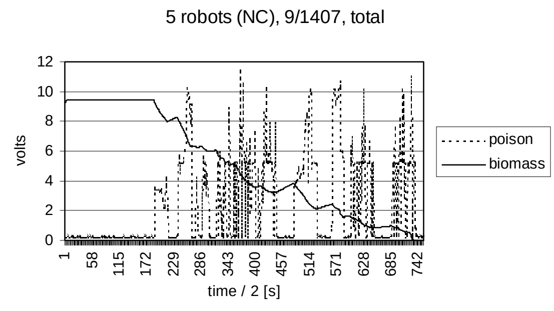

5 robots (NC), 4/1307, total
volts
18
16
14
12
10
8
6
4
2
0
1
85
169
253
337
421
505
589
673
757
841
925
1009
1093
time / 2 [s]
poison
biomass

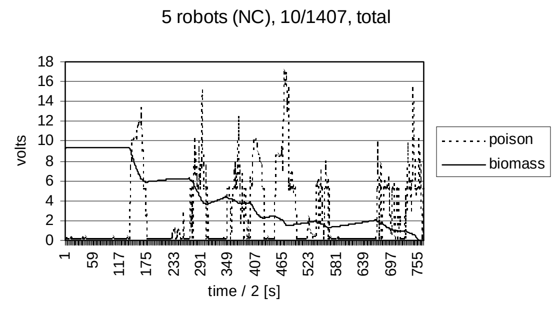

5 robots (NC), 5/1407, total
volts
18
16
14
12
10
8
6
4
2
0
1
65
129
193
257
321
385
449
513
577
641
705
769
833
time / 2 [s]
poison
biomass


5 robots (NC), 6/1407, total
volts
18
16
14
12
10
8
6
4
2
0
1
69
137
205
273
341
409
477
545
613
681
749
817
885
time / 2 [s]
poison
biomass


5 robots (NC), 7/1407, total
volts
25
20
15
10
5
0
1
100
199
298
397
496
595
694
793
892
991
1090
1189
1288
time / 2 [s]
poison
biomass

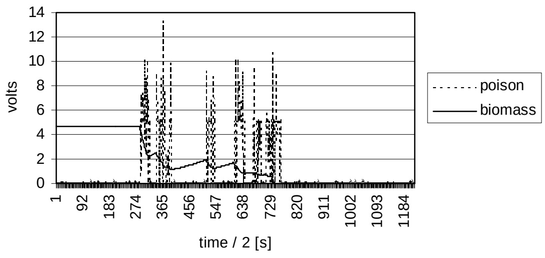

5 robots (NC), 8/1407, total
volts
16
14
12
10
8
6
4
2
0
1
75
149
223
297
371
445
519
593
667
741
815
889
963
time / 2 [s]
poison
biomass


5 robots (NC), 9/1407, total
volts
12
10
8
6
4
2
0
1
58
115
172
229
286
343
400
457
514
571
628
685
742
time / 2 [s]
poison
biomass

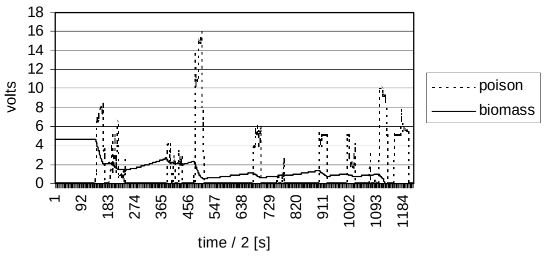

5 robots (NC), 10/1407, total
volts
18
16
14
12
10
8
6
4
2
0
1
59
117
175
233
291
349
407
465
523
581
639
697
755
time / 2 [s]
poison
biomass

Appendix K Tests from Experiment Series I (5 robots, C-type IRC) 1/3

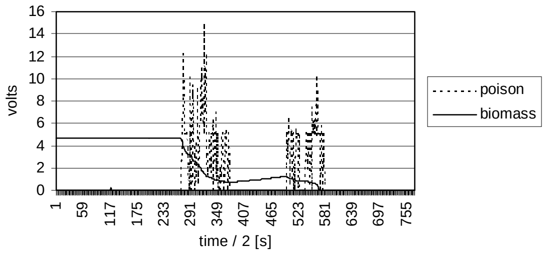
5 robots (C), 1/0707, growth 1



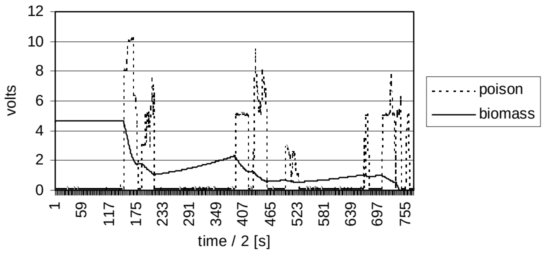
5 robots (C), 1/0707, growth 2



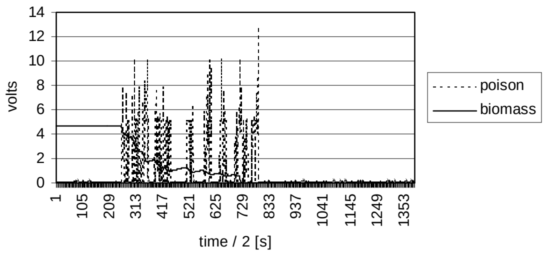
3 robots (C), 2/0707, growth 1



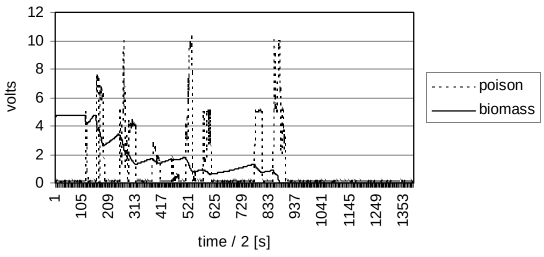
3 robots (C), 2/0707, growth 2



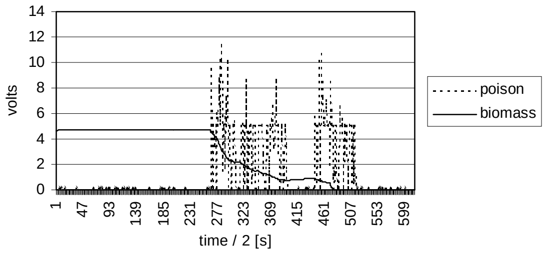
5 robots (C), 3/1207, growth 1



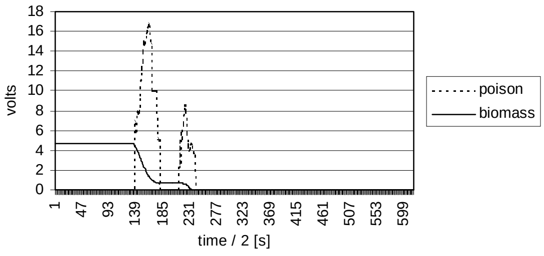
5 robots (C), 3/1207, growth 2



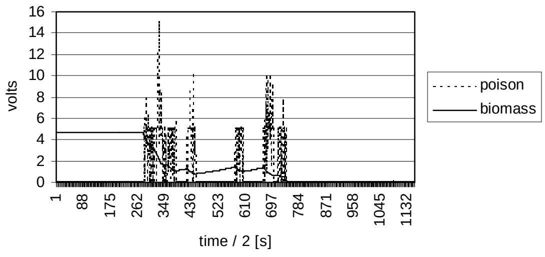
5 robots, (C), 4/11.07, growth 1



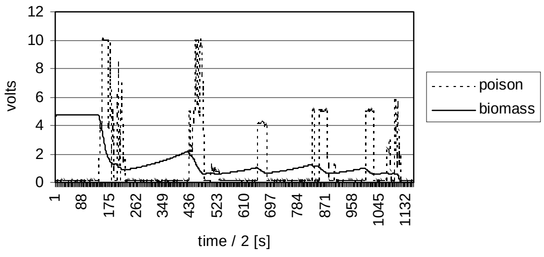
5 robots, (C), 4/11.07, growth 2



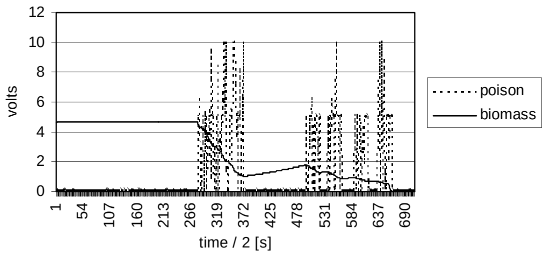
5 robots (C), 5/1207, growth 1



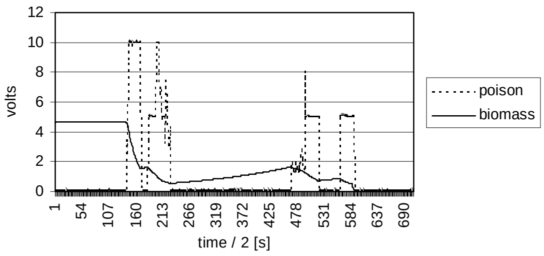
5 robots (C), 5/1207, growth 2



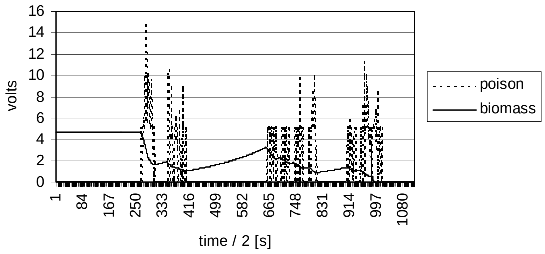
5 robots (C), 6/1207, growth 1



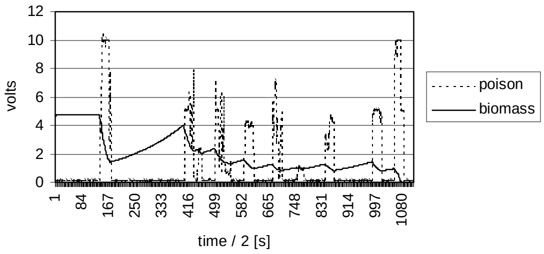
5 robots (C), 6/1207, growth 2



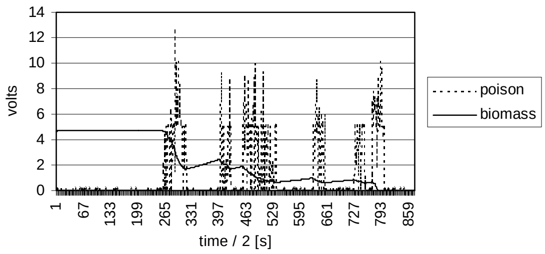
5 robots (C), 7/1207, growth 1



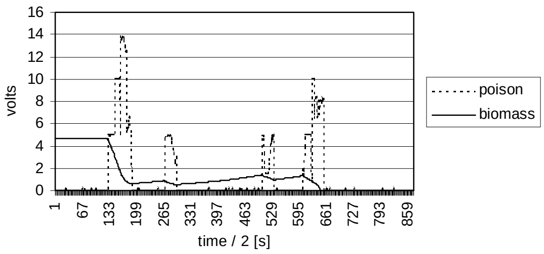
5 robots (C), 7/1207, growth 2



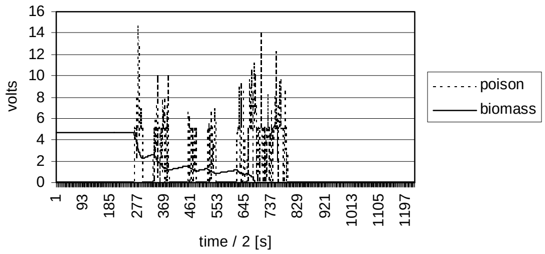
5 robots (C), 8/1207, growth 1



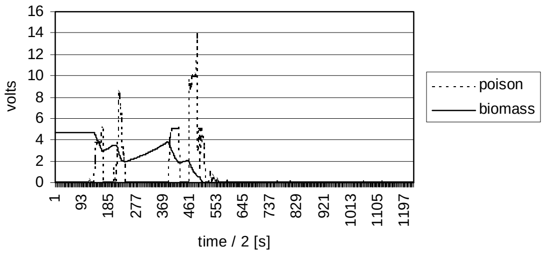
5 robots (C), 8/1207, growth 2



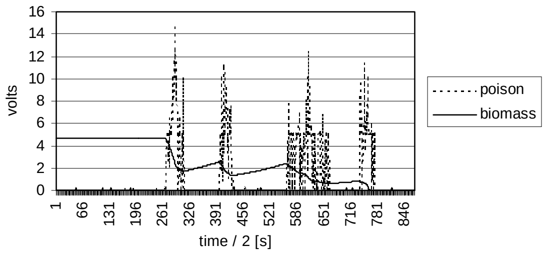
5 robots (C), 9/1307, growth 1



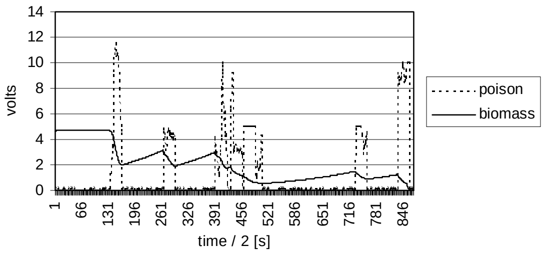
5 robots (C), 9/1307, growth 2

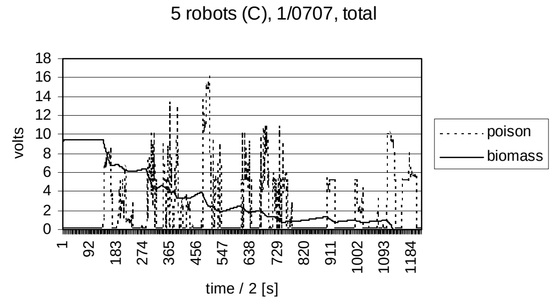


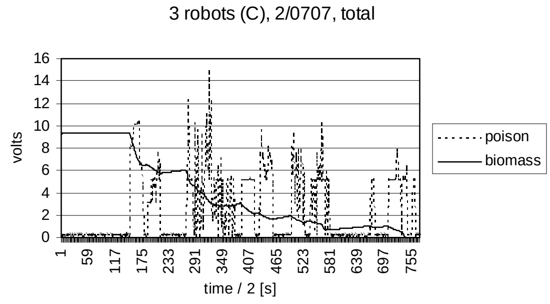
5 robots (C), 10/1307, growth 1

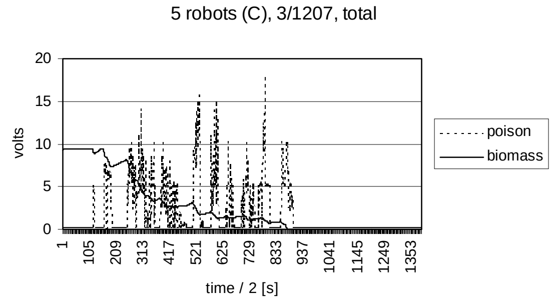


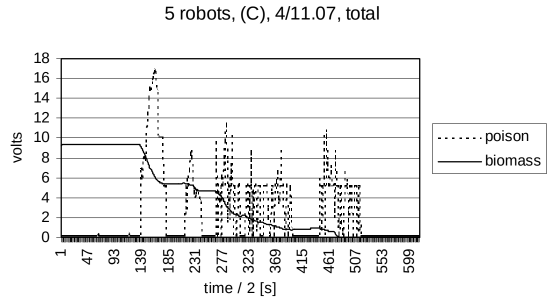
5 robots (C), 10/1307, growth 2

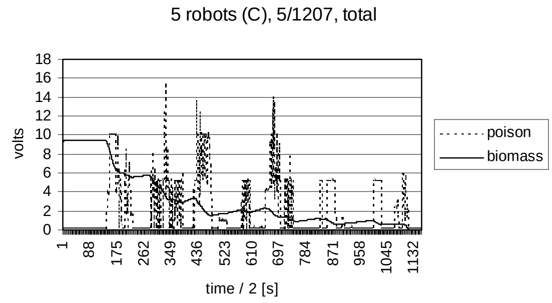


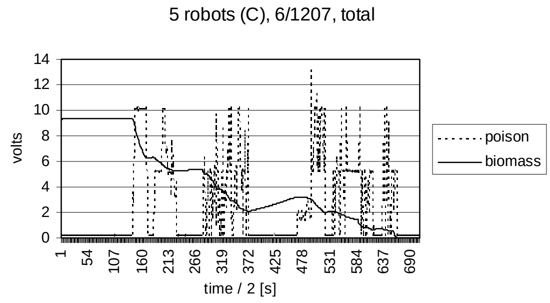

5 robots (C), 1/0707, total

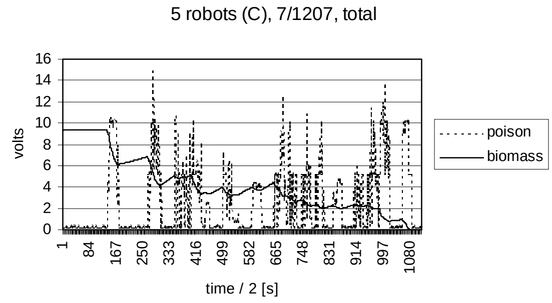

3 robots (C), 2/0707, total

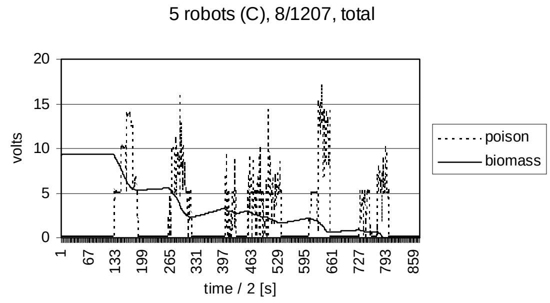

5 robots (C), 3/1207, total

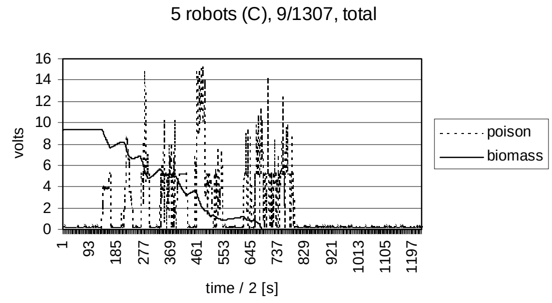

5 robots, (C), 4/11.07, total

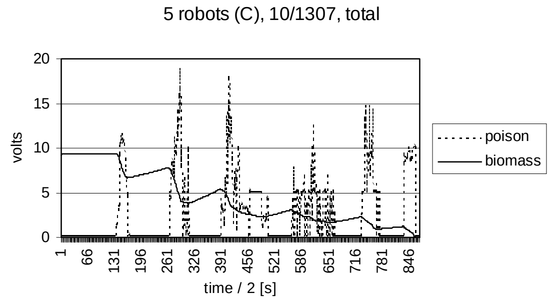

5 robots (C), 5/1207, total


5 robots (C), 6/1207, total

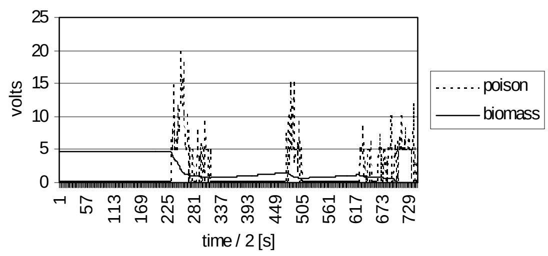

5 robots (C), 7/1207, total

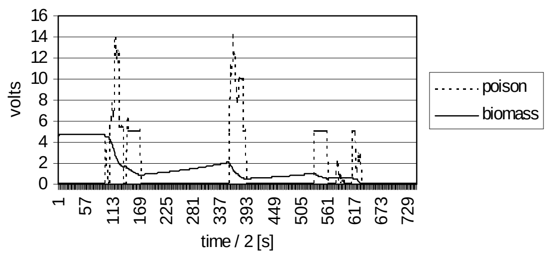

5 robots (C), 8/1207, total

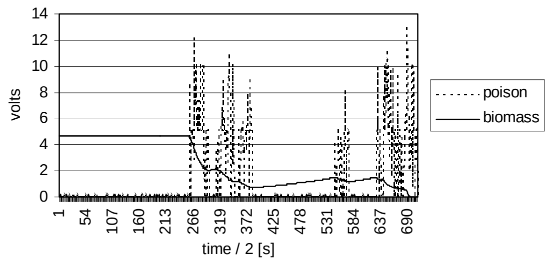

5 robots (C), 9/1307, total

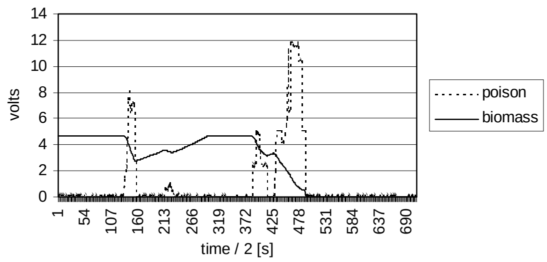

5 robots (C), 10/1307, total

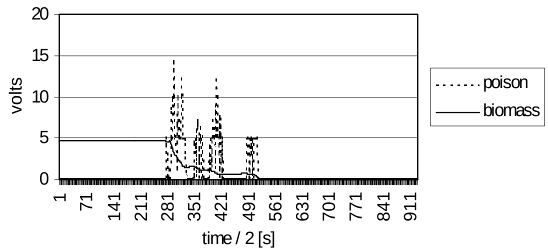
Appendix L Tests from Experiment Series I (5 robots, CC-type IRC) 1/3

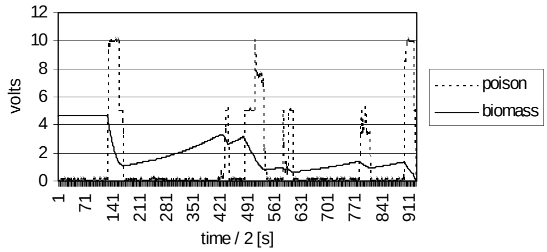

5 robots (CC), 1/2007, growth 1

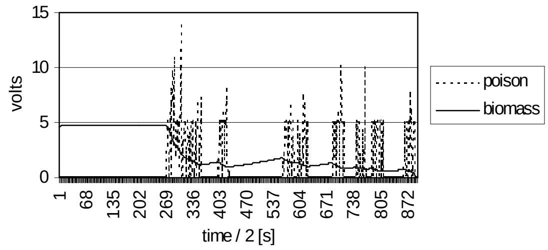

5 robots (CC), 1/2007, growth 2

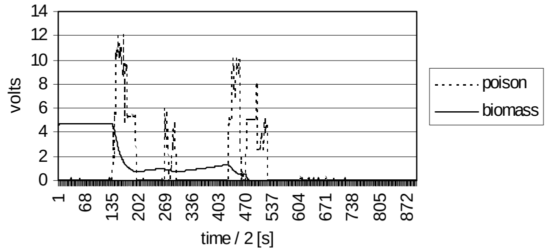

5 robots (CC), 2/2107, growth 1

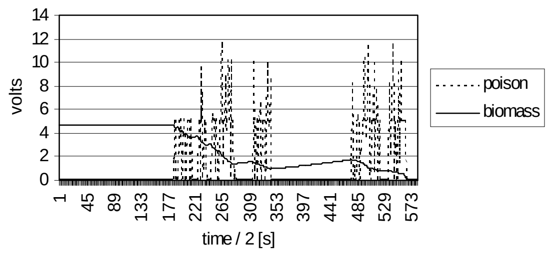

5 robots (CC), 2/2107, growth 2

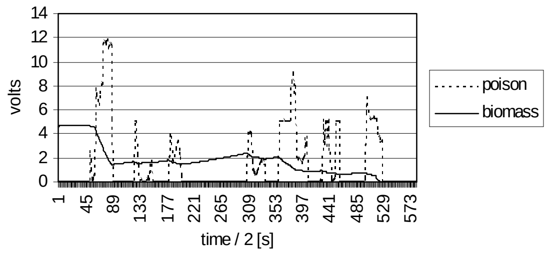

5 robots (CC), 3/2007, growth 1


5 robots (CC), 3/2007, growth 2


5 robots (CC), 4/2007, growth 1

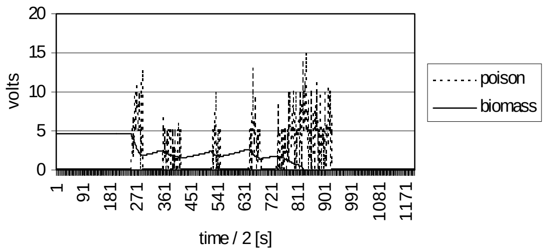

5 robots (CC), 4/2007, growth 2


5 robots (CC), 5/2107, growth 1

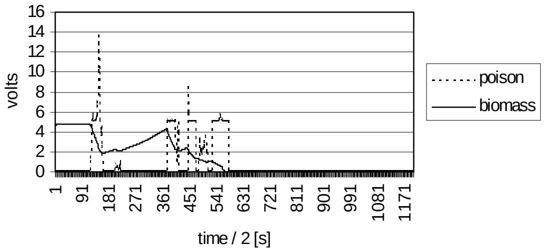

5 robots (CC), 5/2107, growth 2

Appendix L Tests from Experiment Series I (5 robots, CC-type IRC) 2/3

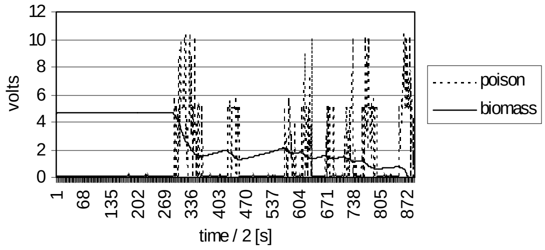
5 robots (CC), 6/21.07, growth 1



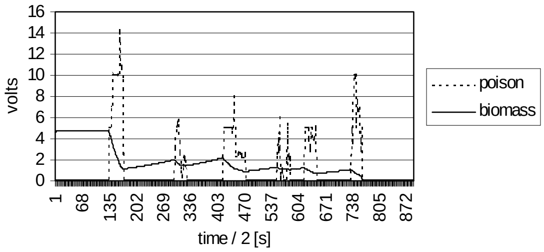
5 robots (CC), 6/21.07, growth 2



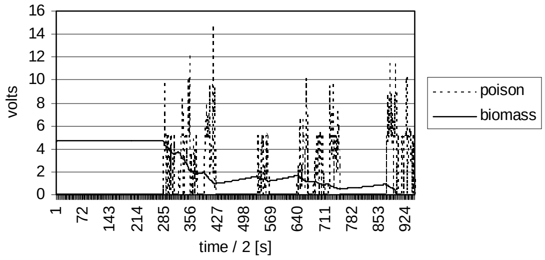
5 robots (CC), 7/2107, growth 1



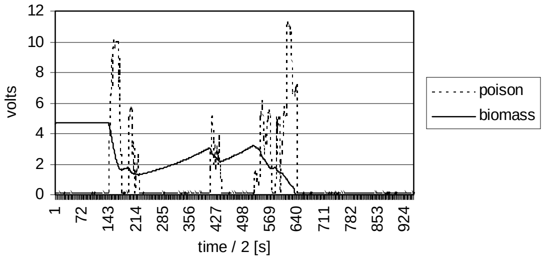
5 robots (CC), 7/2107, growth 2



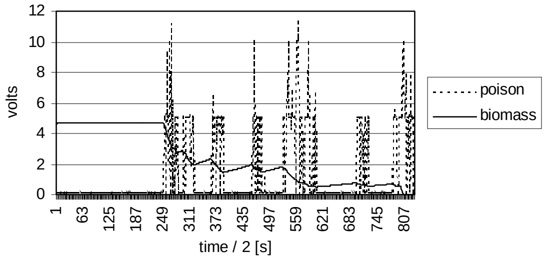
5 robots (CC), 8/2107, growth 1



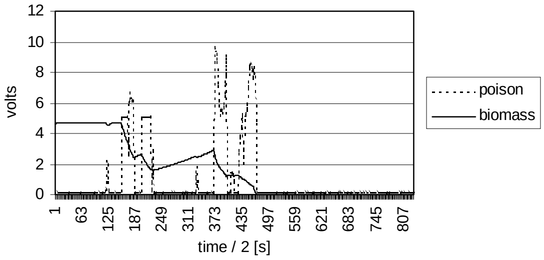
5 robots (CC), 8/2107, growth 2



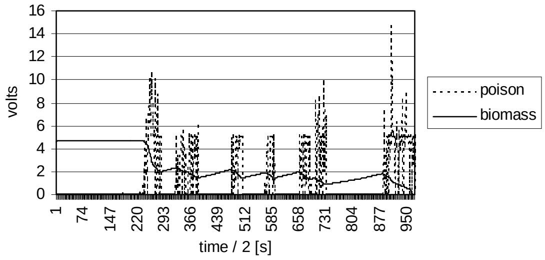
5 robots (CC), 9/2207, growth 1



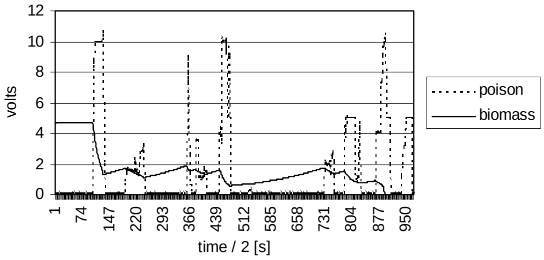
5 robots (CC), 9/2207, growth 2

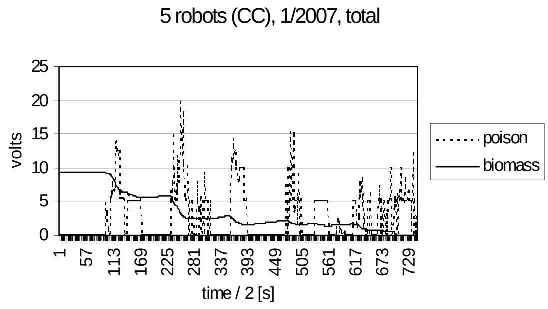


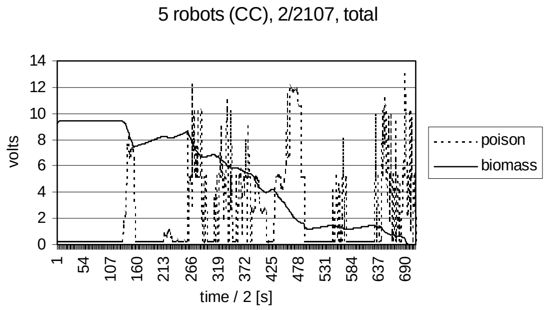
5 robots (CC), 10/2307, growth 1

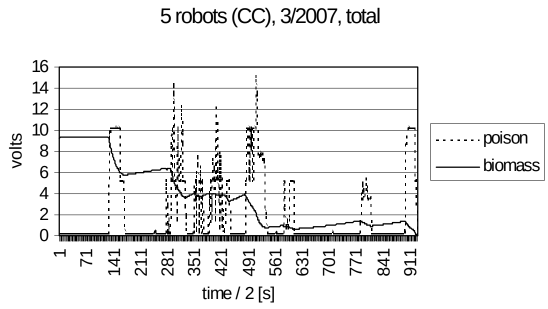


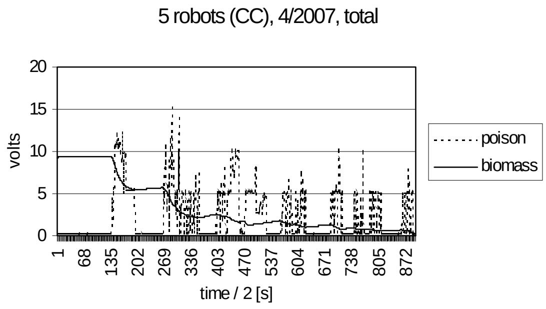
5 robots (CC), 10/2307, growth 2

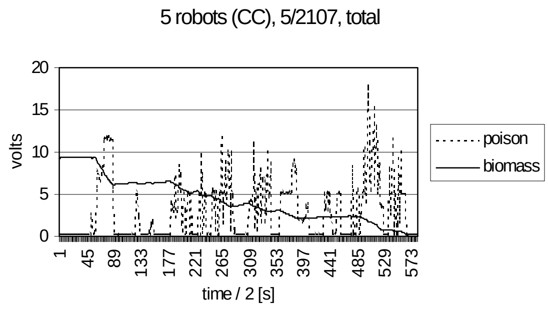


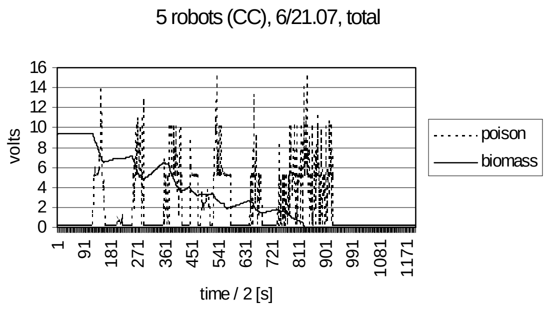

5 robots (CC), 1/2007, total

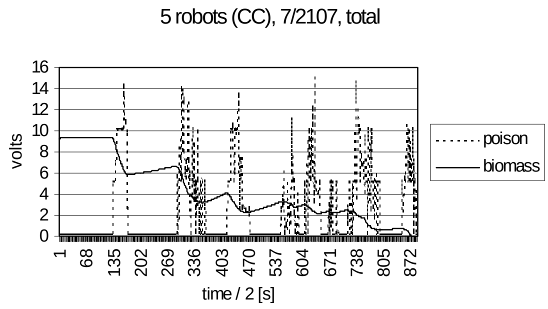

5 robots (CC), 2/2107, total

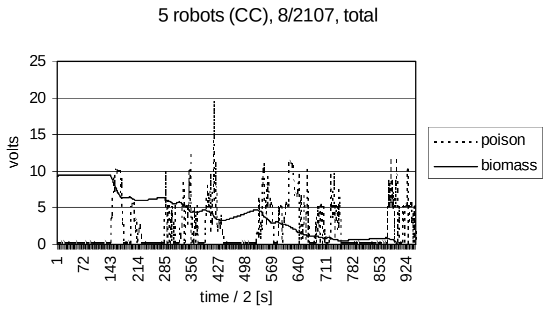

5 robots (CC), 3/2007, total

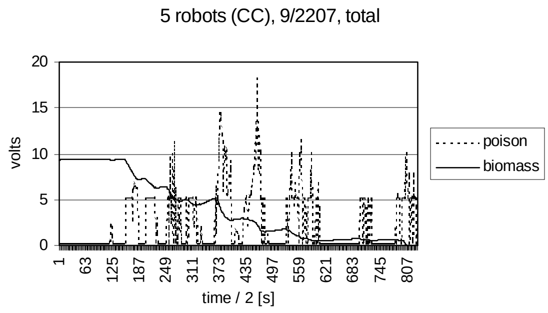

5 robots (CC), 4/2007, total

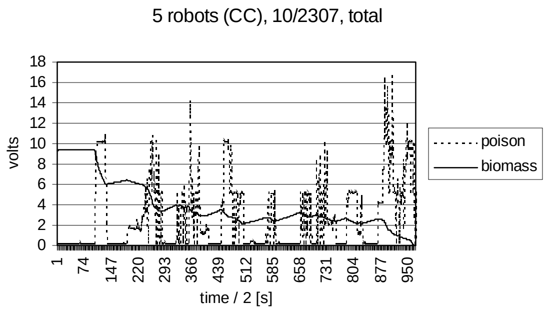

5 robots (CC), 5/2107, total


5 robots (CC), 6/21.07, total


5 robots (CC), 7/2107, total

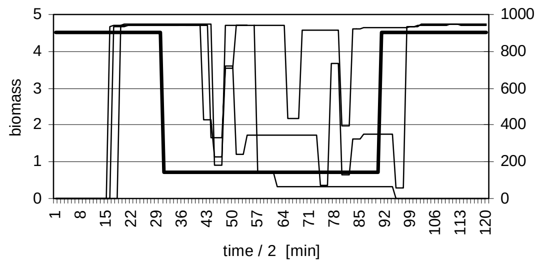

5 robots (CC), 8/2107, total


5 robots (CC), 9/2207, total

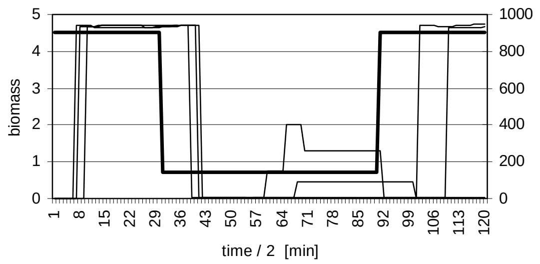

5 robots (CC), 10/2307, total

Appendix M Tests from Experiment Series II (3 robots, no IRC)

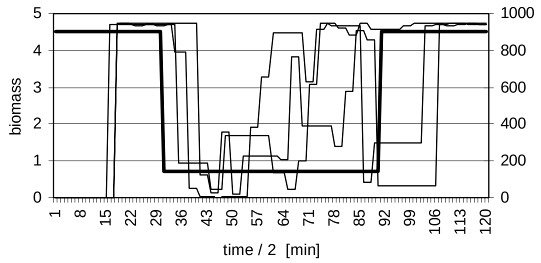
3 robots (nc), run 1, growth 1



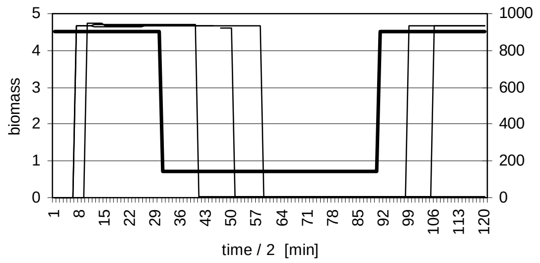
3 robots (nc), run 1, growth 2



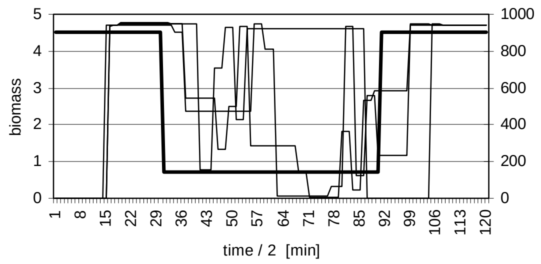
3 robots (nc), run 2, growth 1



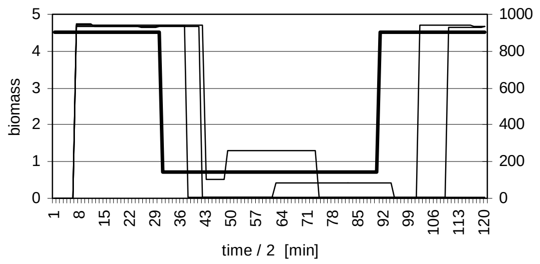
3 robots (nc), run 2, growth 2



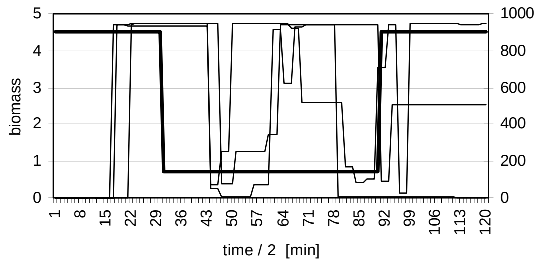
3 robots (nc), run 3, growth 1



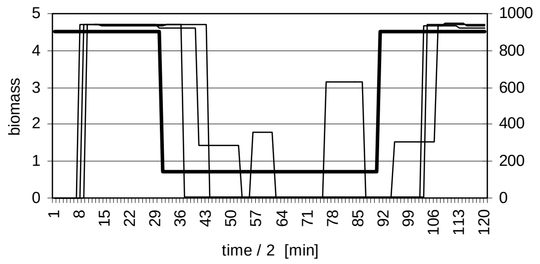
3 robots (nc), run 3, growth 2



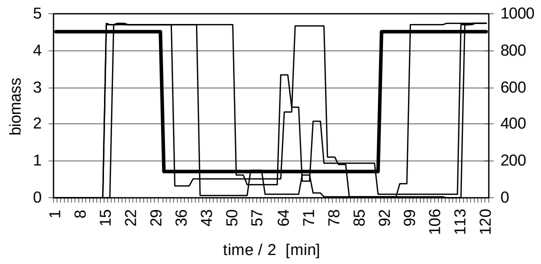
3 robots (nc), run 4, growth 1



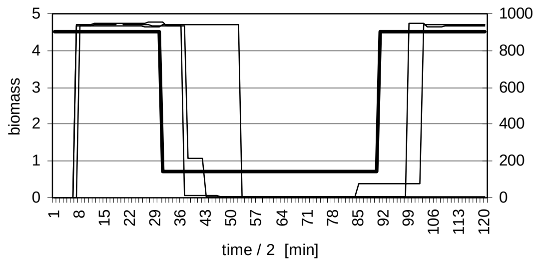
3 robots (nc), run 4, growth 2



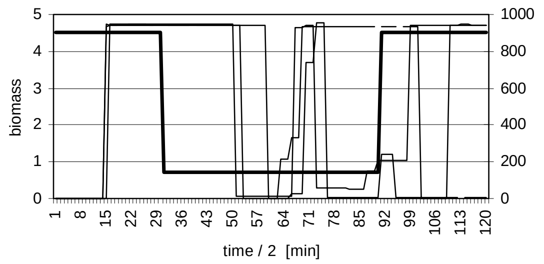
3 robots (nc), run 5, growth 1



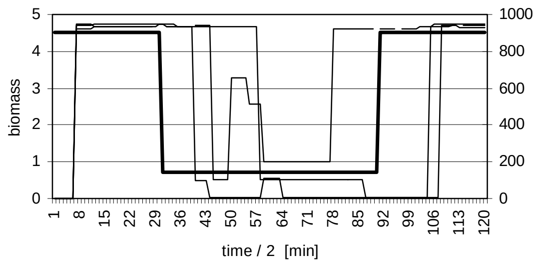
3 robots (nc), run 5, growth 2



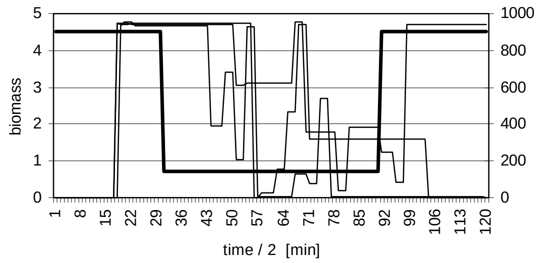
3 robots (nc), run 6, growth 1



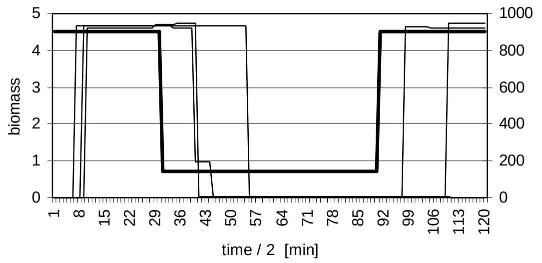
3 robots (nc), run 6, growth 2



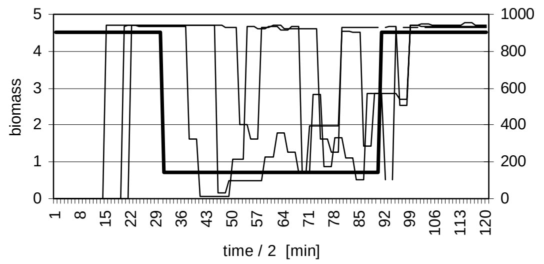
3 robots (nc), run 7, growth 1



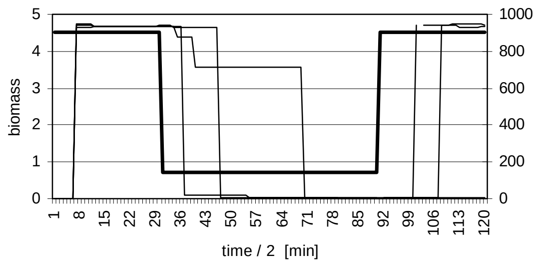
3 robots (nc), run 7, growth 2



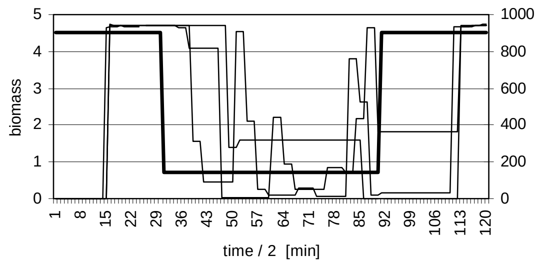
3 robots (nc), run 8, growth 1



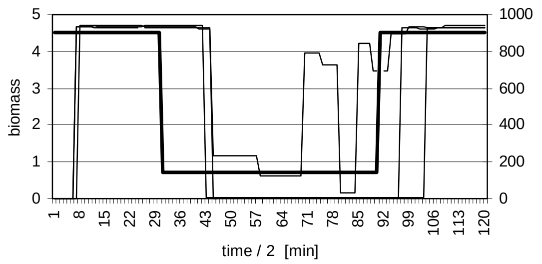
3 robots (nc), run 8, growth 2



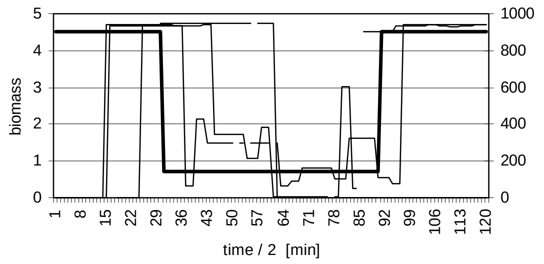
3 robots (nc), run 9, growth 1



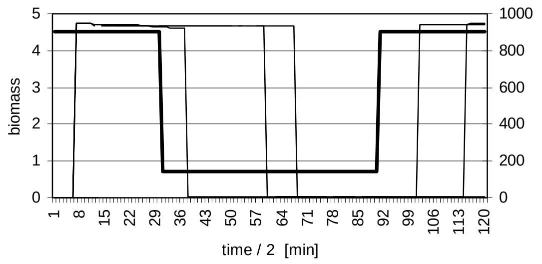
3 robots (nc), run 9, growth 2



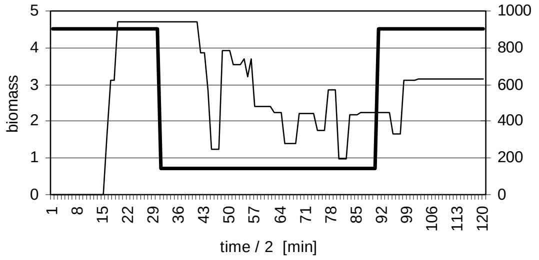
3 robots (nc), run 10, growth 1



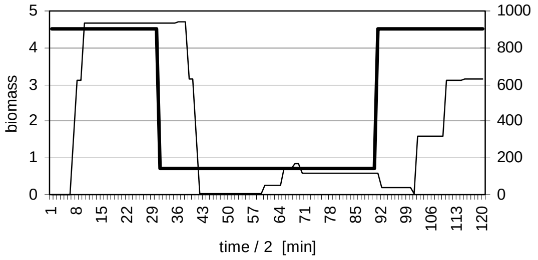
3 robots (nc), run 10, growth 2



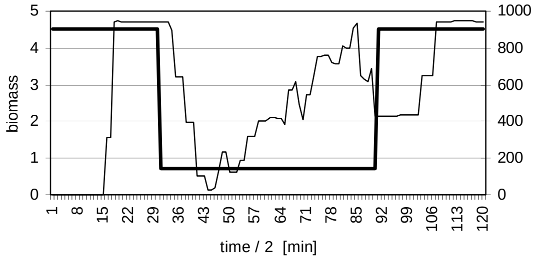
3 robots (nc), run 1, growth 1, average



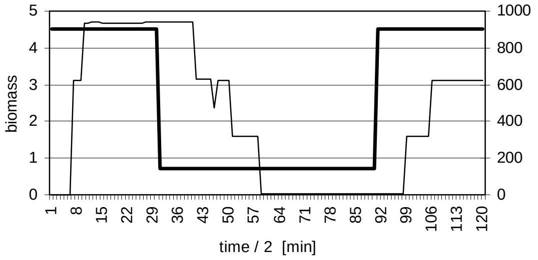
3 robots (nc), run 1, growth 2, average



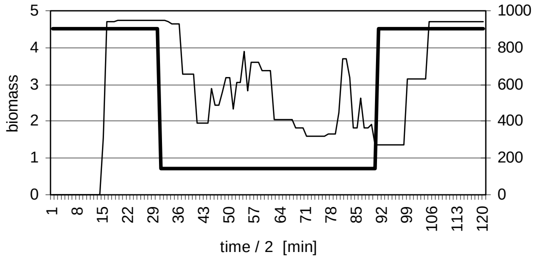
3 robots (nc), run 2, growth 1, average



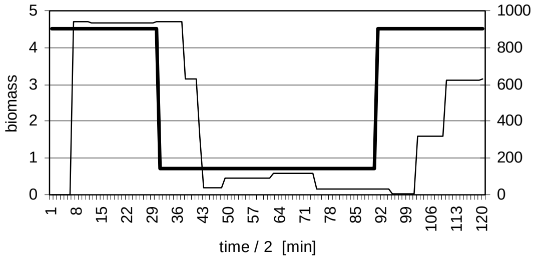
3 robots (nc), run 2, growth 2, average



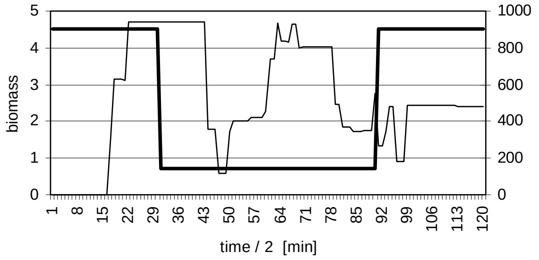
3 robots (nc), run 3, growth 1, average



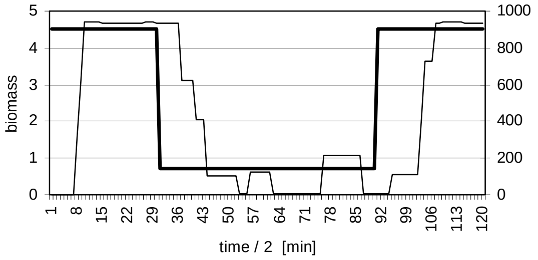
3 robots (nc), run 3, growth 2, average



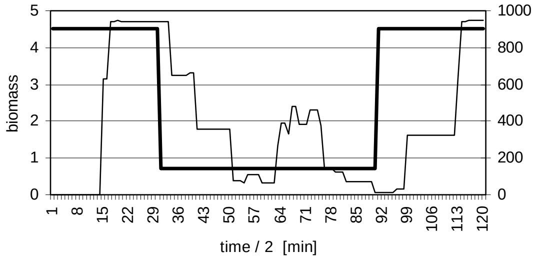
3 robots (nc), run 4, growth 1, average



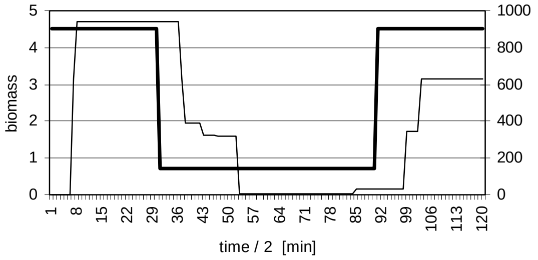
3 robots (nc), run 4, growth 2, average



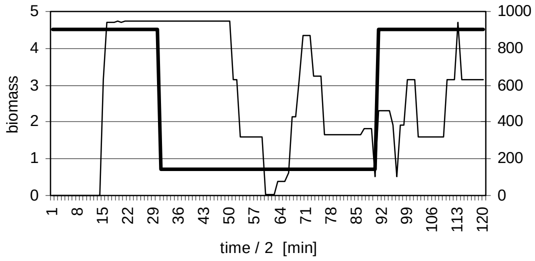
3 robots (nc), run 5, growth 1, average



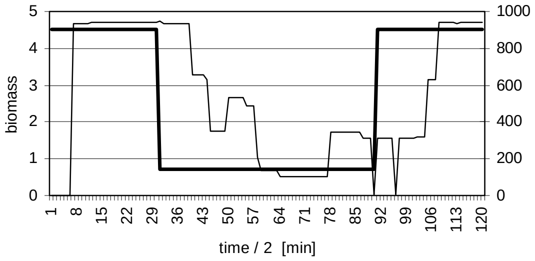
3 robots (nc), run 5, growth 2, average



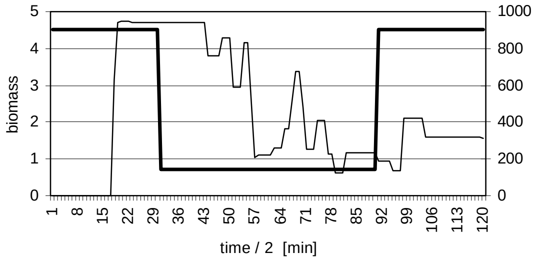
3 robots (nc), run 6, growth 1, average



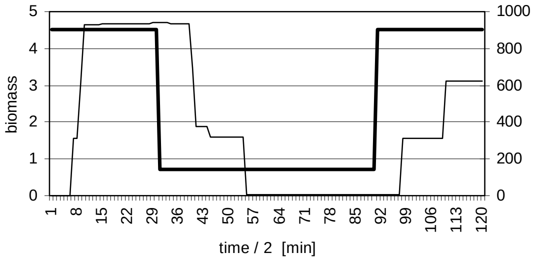
3 robots (nc), run 6, growth 2, average



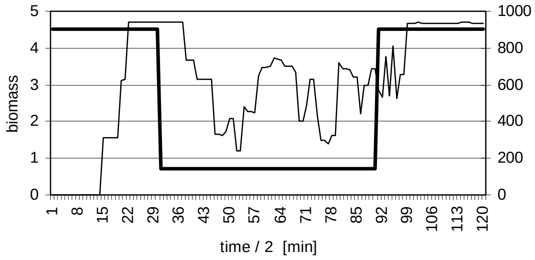
3 robots (nc), run 7, growth 1, average



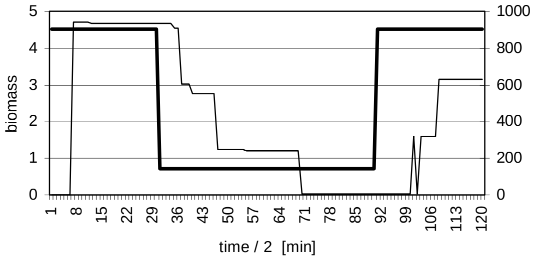
3 robots (nc), run 7, growth 2, average



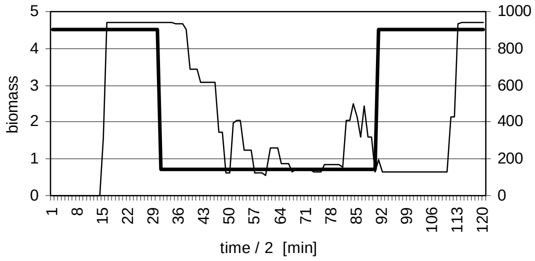
3 robots (nc), run 8, growth 1, average



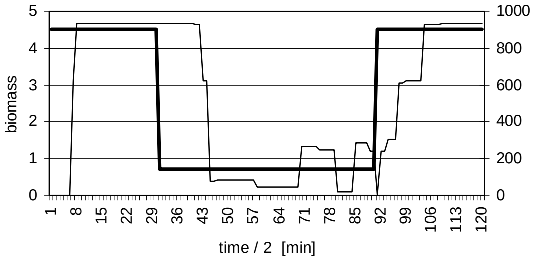
3 robots (nc), run 8, growth 2, average



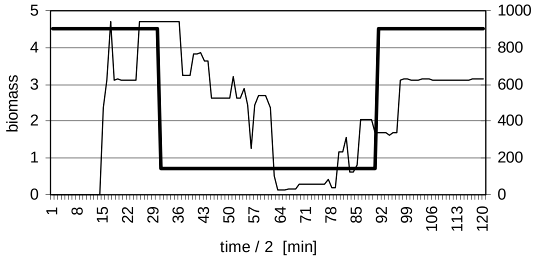
3 robots (nc), run 9, growth 1, average



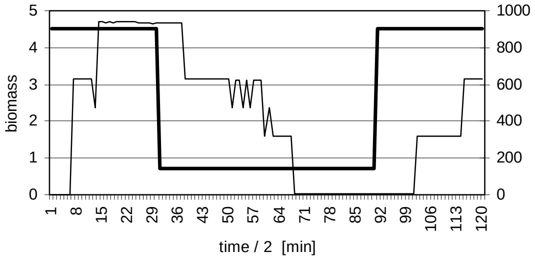
3 robots (nc), run 9, growth 2, average



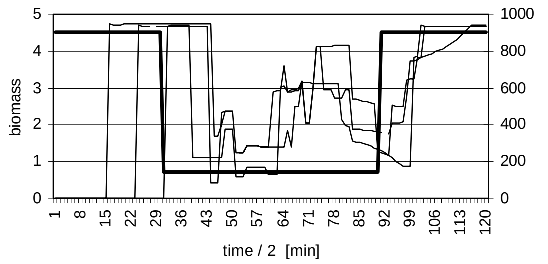
3 robots (nc), run 10, growth 1, average



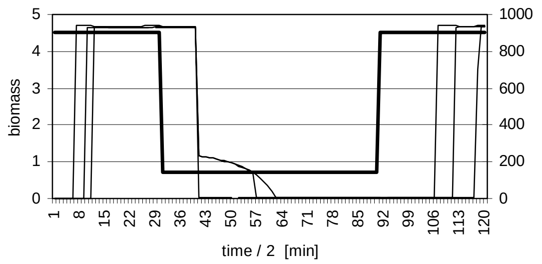
3 robots (nc), run 10, growth 2, average



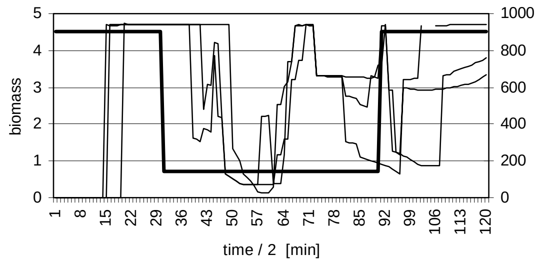
3 robots (cc), run 1, growth 1



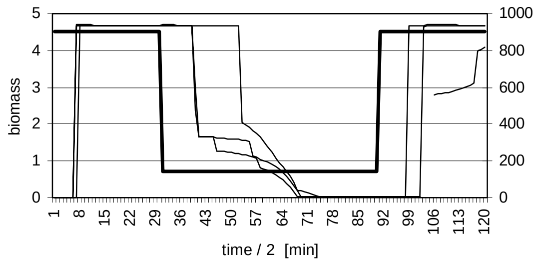
3 robots (cc), run 1, growth 2



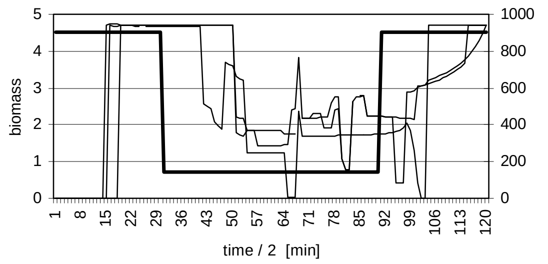
3 robots (cc), run 2, growth 1



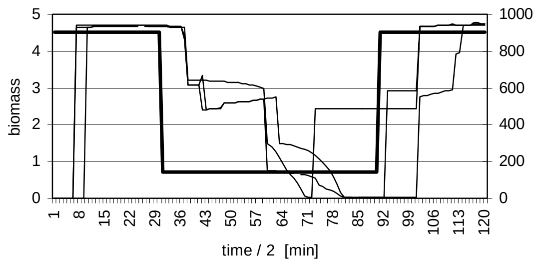
3 robots (cc), run 2, growth 2



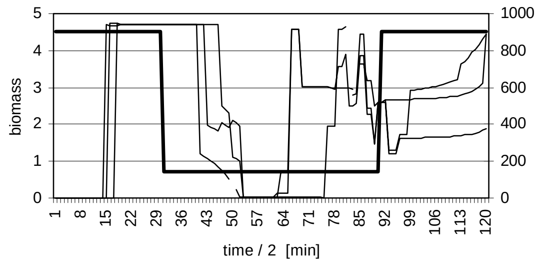
3 robots (cc), run 3, growth 1



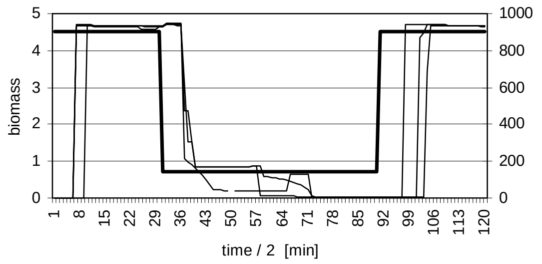
3 robots (cc), run 3, growth 2



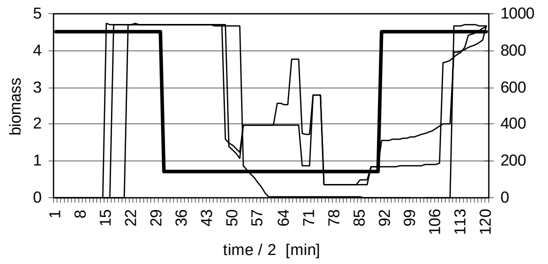
3 robots (cc), run 4, growth 1



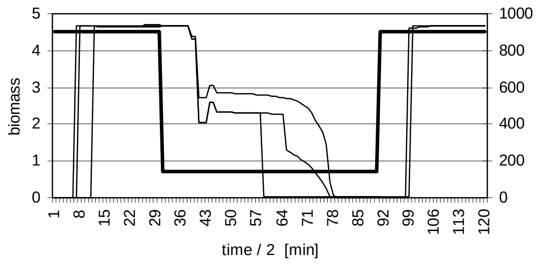
3 robots (cc), run 4, growth 2



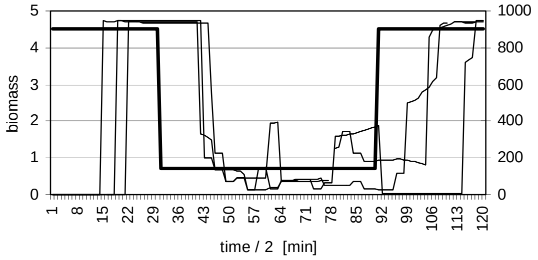
3 robots (cc), run 5, growth 1



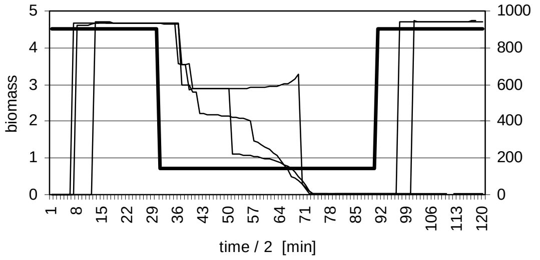
3 robots (cc), run 5, growth 2



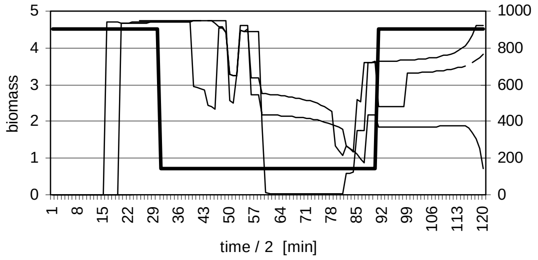
3 robots (cc), run 6, growth 1



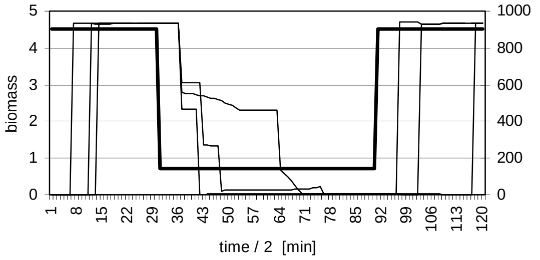
3 robots (cc), run 6, growth 2



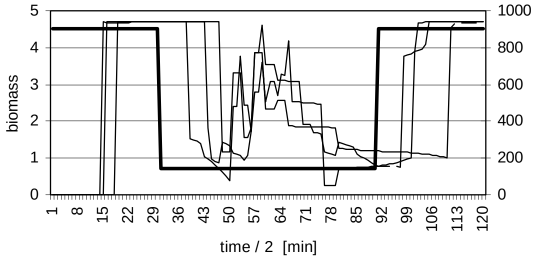
3 robots (cc), run 7, growth 1



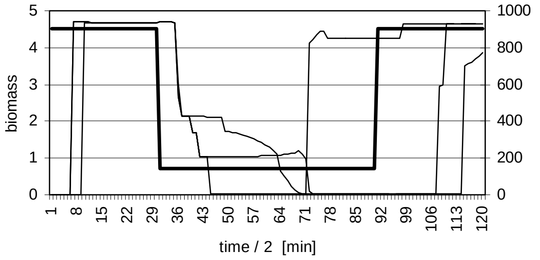
3 robots (cc), run 7, growth 2



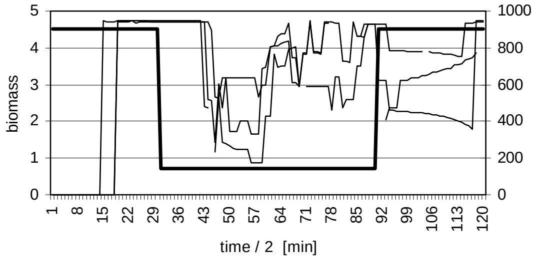
3 robots (cc), run 8, growth 1



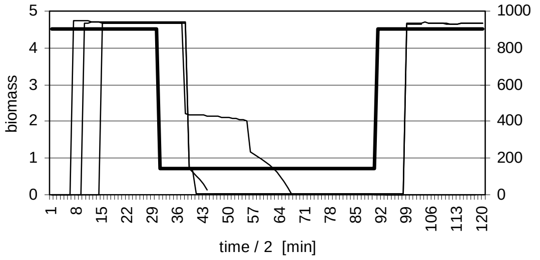
3 robots (cc), run 8, growth 2



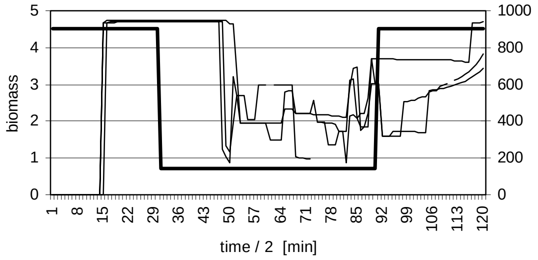
3 robots (cc), run 9, growth 1



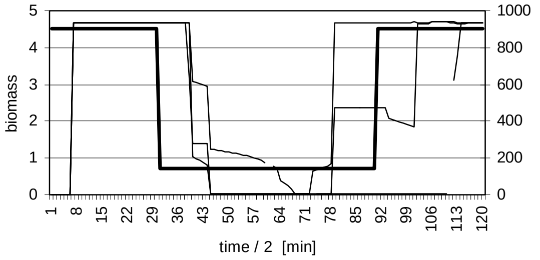
3 robots (cc), run 9, growth 2



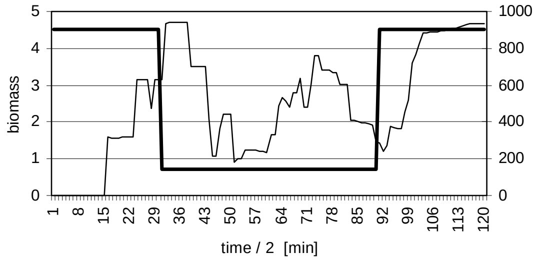
3 robots (cc), run 10, growth 1



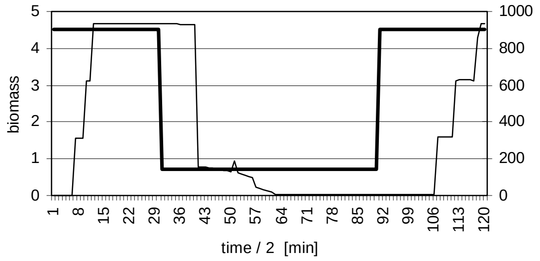
3 robots (cc), run 10, growth 2



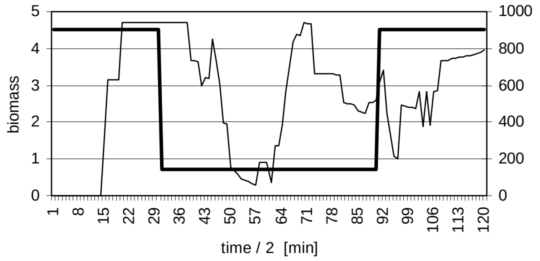
3 robots (cc), run 1, growth 1, average



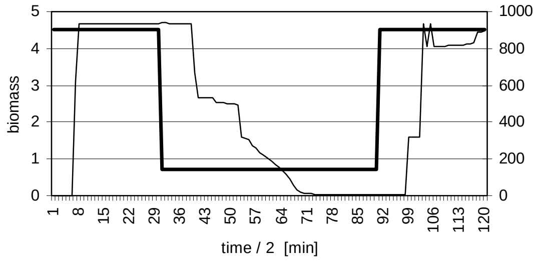
3 robots (cc), run 1, growth 2, average



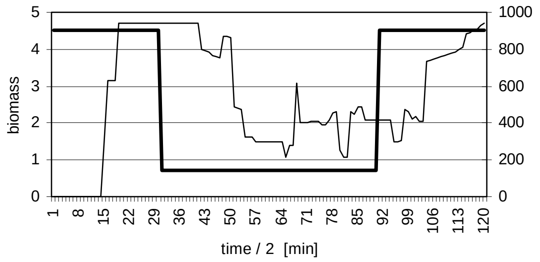
3 robots (cc), run 2, growth 1, average



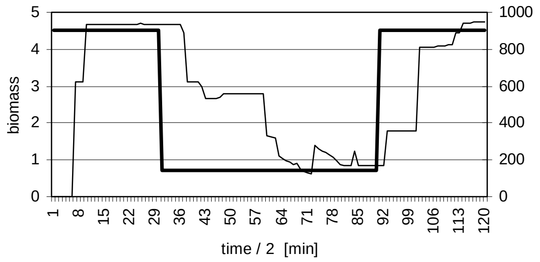
3 robots (cc), run 2, growth 2, average



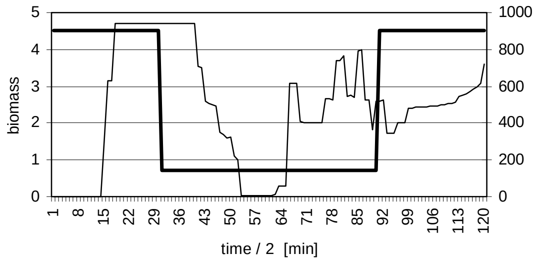
3 robots (cc), run 3, growth 1, average



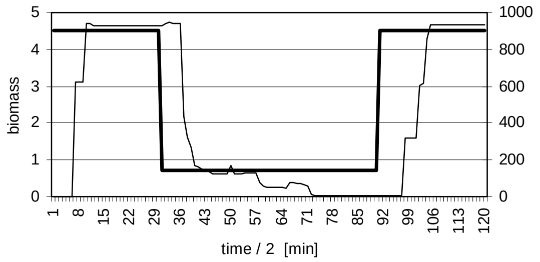
3 robots (cc), run 3, growth 2, average



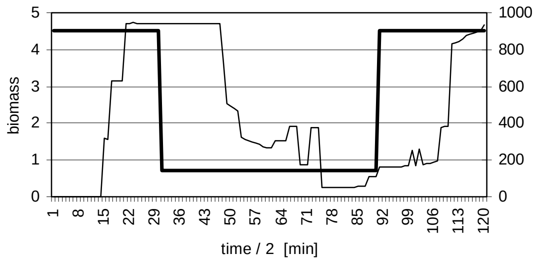
3 robots (cc), run 4, growth 1, average



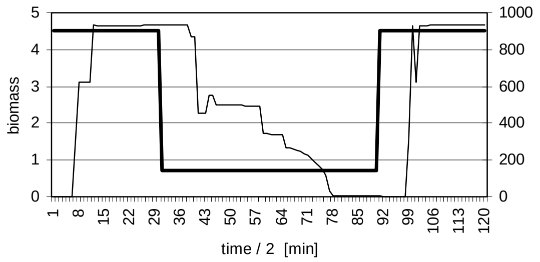
3 robots (cc), run 4, growth 2, average



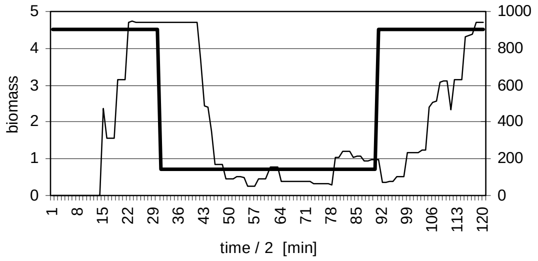
3 robots (cc), run 5, growth 1, average



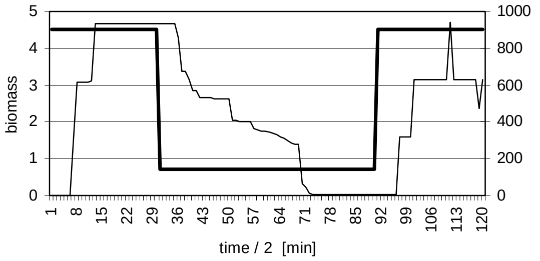
3 robots (cc), run 5, growth 2, average



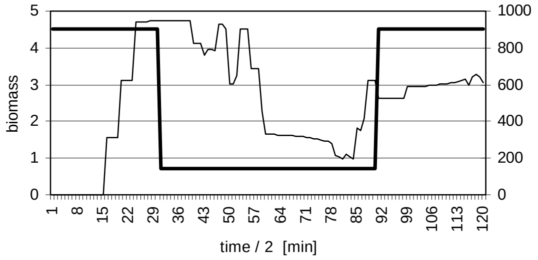
3 robots (cc), run 6, growth 1, average



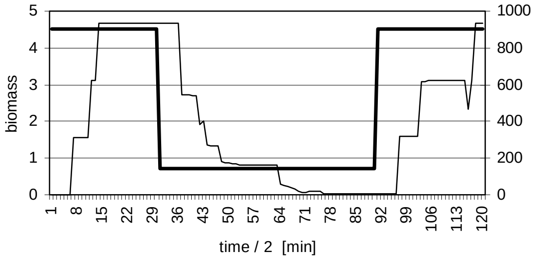
3 robots (cc), run 6, growth 2, average



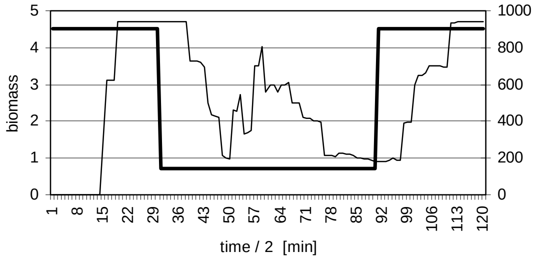
3 robots (cc), run 7, growth 1, average



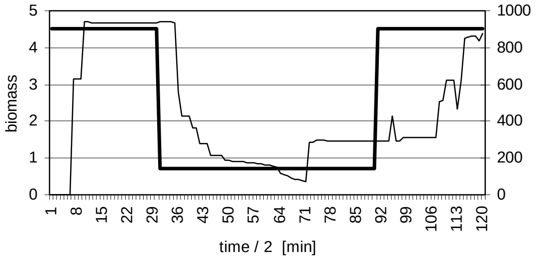
3 robots (cc), run 7, growth 2, average



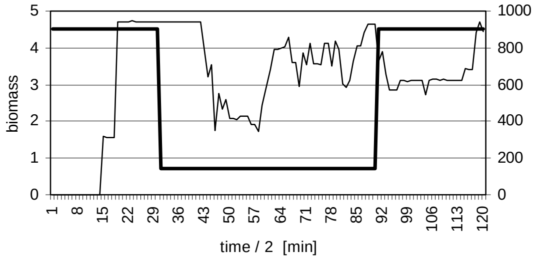
3 robots (cc), run 8, growth 1, average



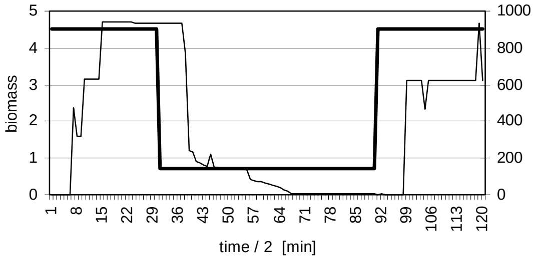
3 robots (cc), run 8, growth 2, average



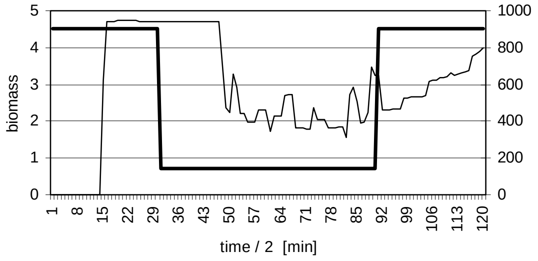
3 robots (cc), run 9, growth 1, average



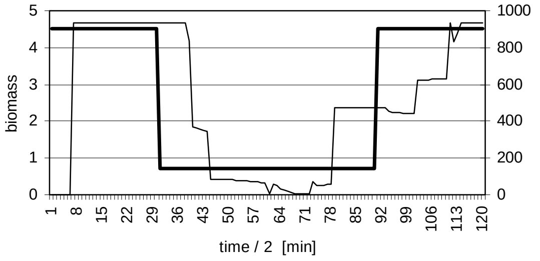
3 robots (cc), run 9, growth 2, average



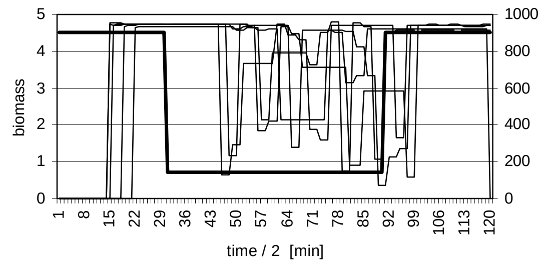
3 robots (cc), run 10, growth 1, average

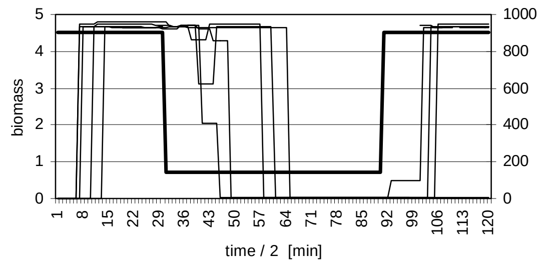


3 robots (cc), run 10, growth 2, average



Appendix O Tests from Experiment Series II (5 robots, no IRC) 1/4


5 robots (nc), run 1, growth 1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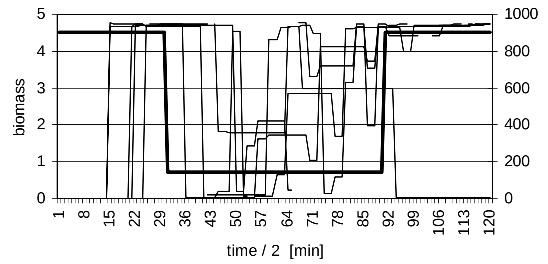
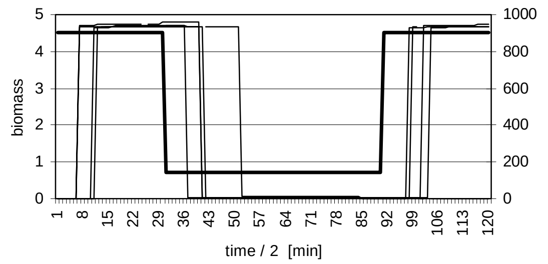
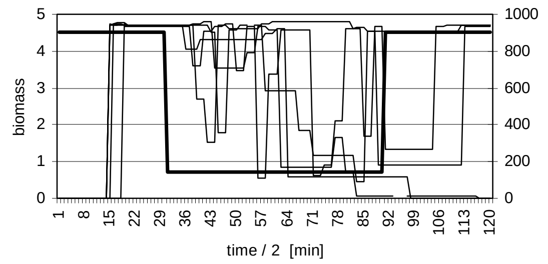
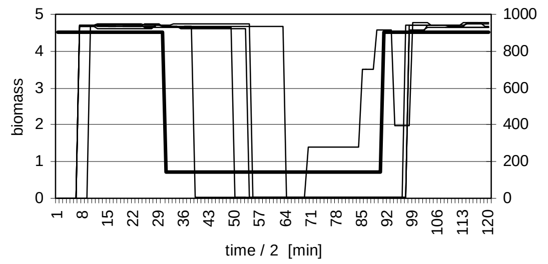
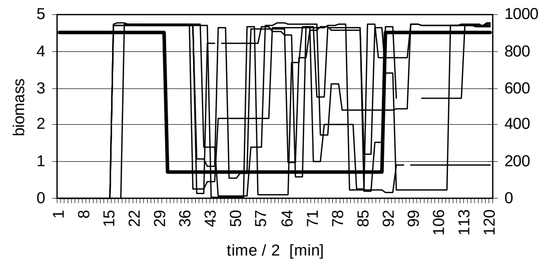
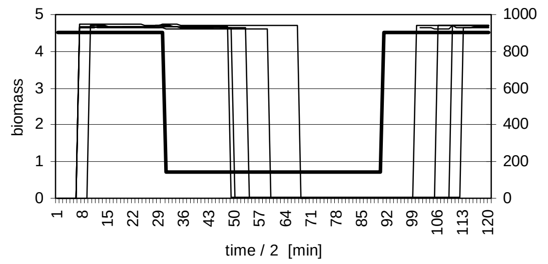

5 robots (nc), run 2, growth 1

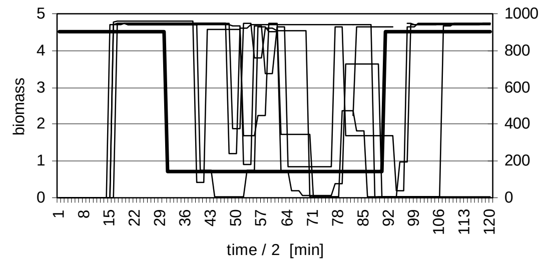

5 robots (nc), run 2, growth 2

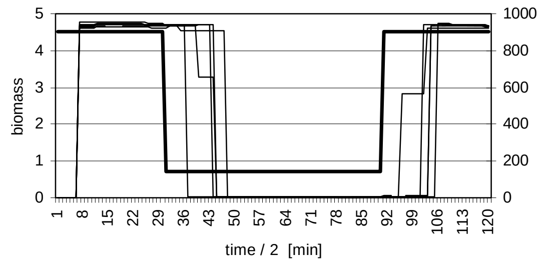

5 robots (nc), run 3, growth 1


5 robots (nc), run 3, growth 2

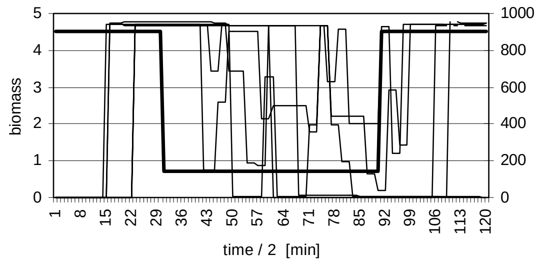

5 robots (nc), run 4, growth 1


5 robots (nc), run 4, growth 2

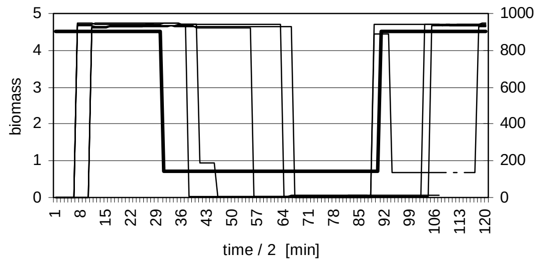

5 robots (nc), run 5, growth 1


5 robots (nc), run 5, growth 2

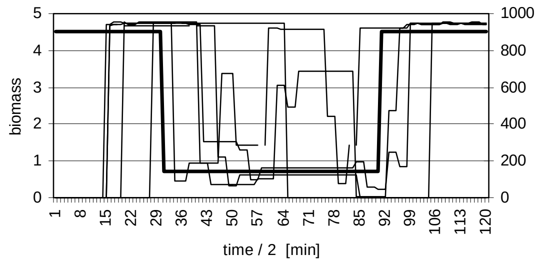
5 robots (nc), run 6, growth 1



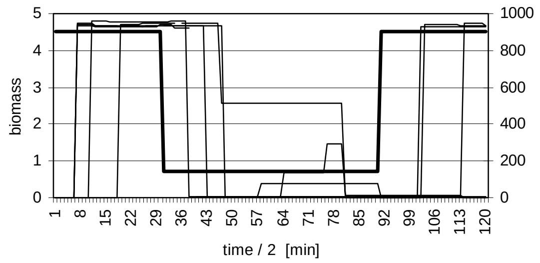
5 robots (nc), run 6, growth 2



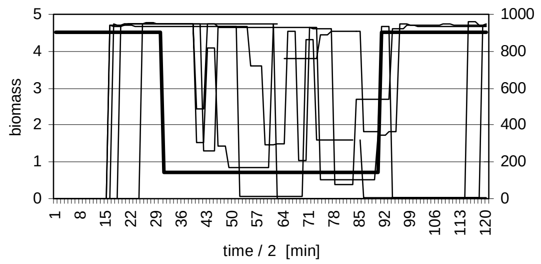
5 robots (nc), run 7, growth 1



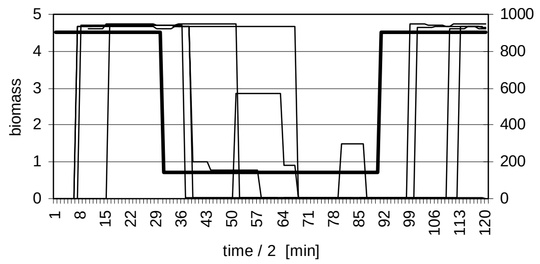
5 robots (nc), run 7, growth 2



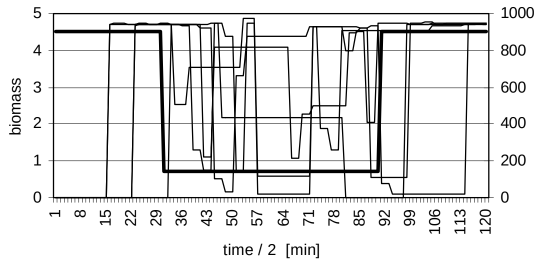
5 robots (nc), run 8, growth 1



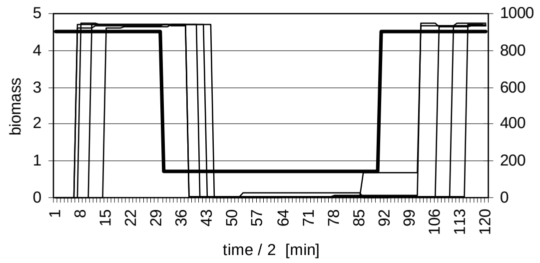
5 robots (nc), run 8, growth 2



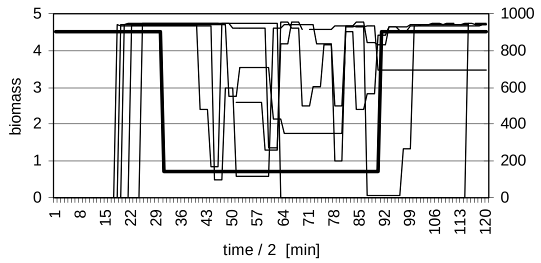
5 robots (nc), run 9, growth 1



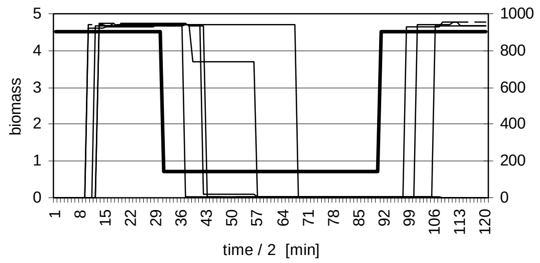
5 robots (nc), run 9, growth 2

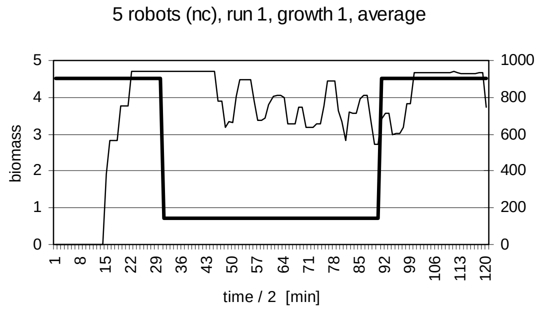


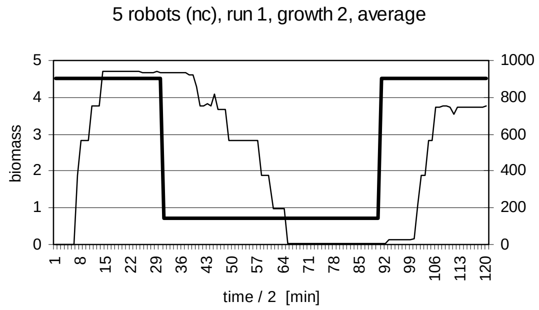
5 robots (nc), run 10, growth 1

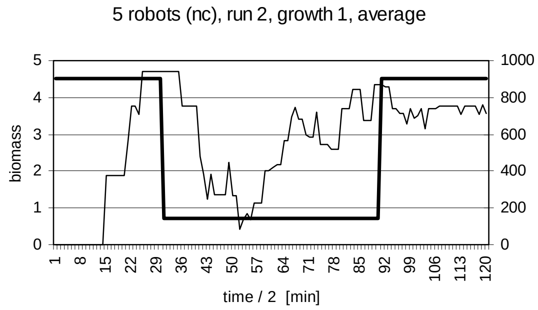


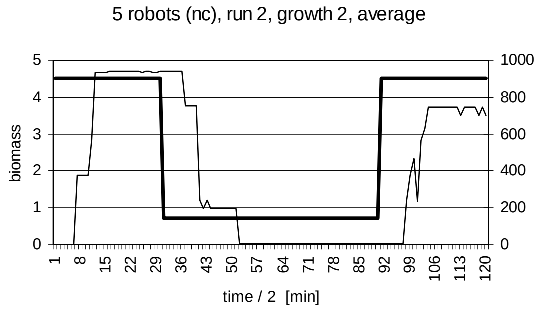
5 robots (nc), run 10, growth 2

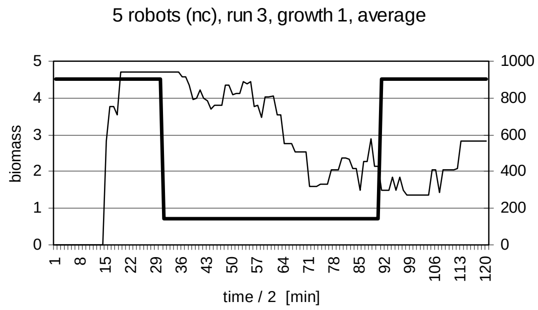


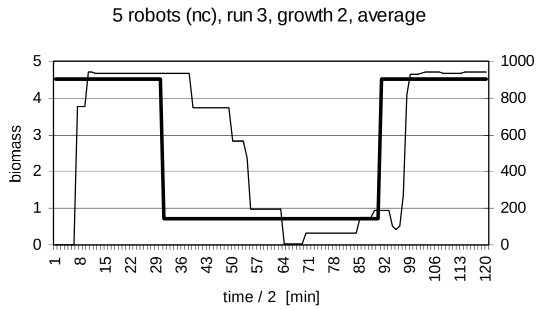

5 robots (nc), run 1, growth 1, average

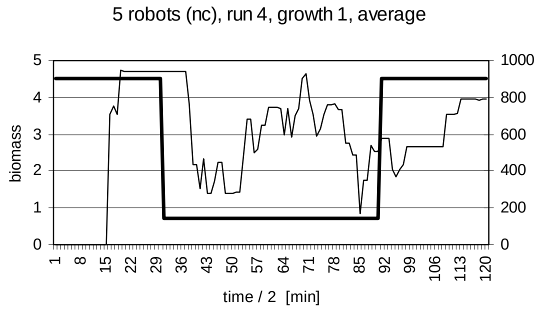

5 robots (nc), run 1, growth 2, average

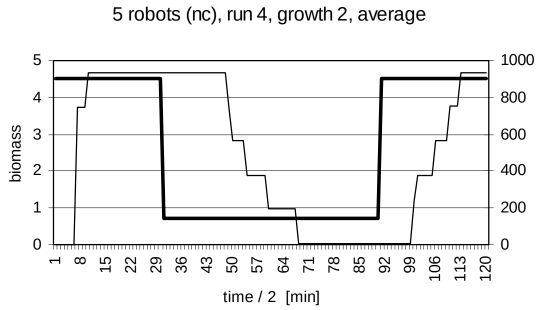

5 robots (nc), run 2, growth 1, average

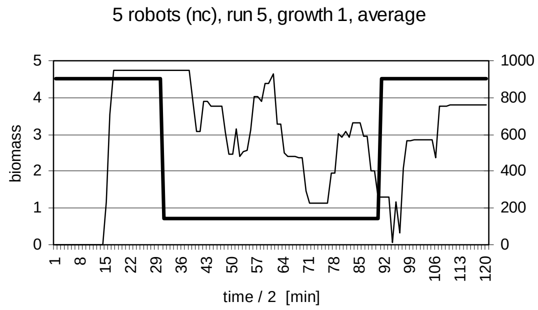

5 robots (nc), run 2, growth 2, average

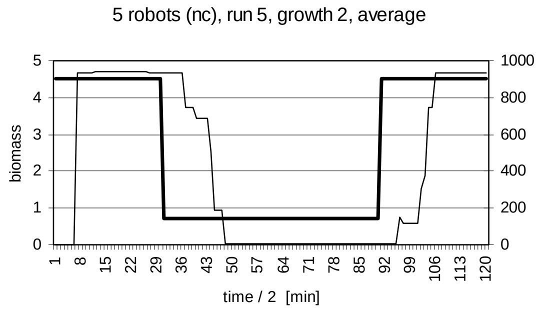

5 robots (nc), run 3, growth 1, average

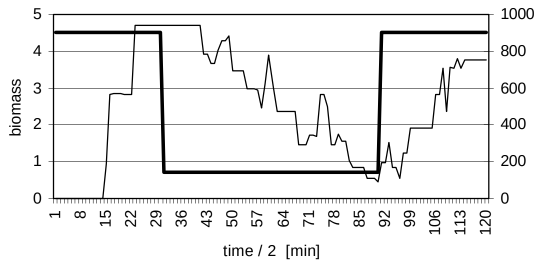

5 robots (nc), run 3, growth 2, average

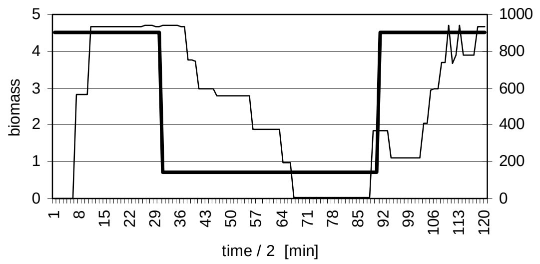

5 robots (nc), run 4, growth 1, average

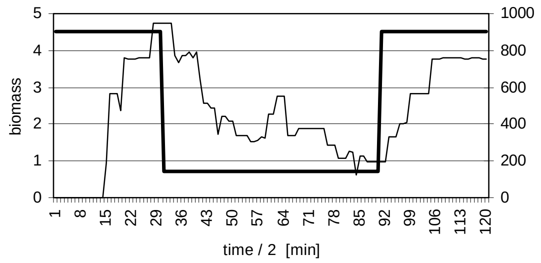

5 robots (nc), run 4, growth 2, average

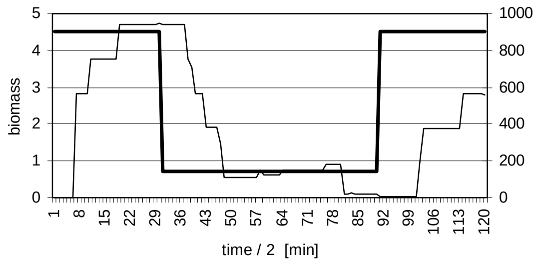

5 robots (nc), run 5, growth 1, average

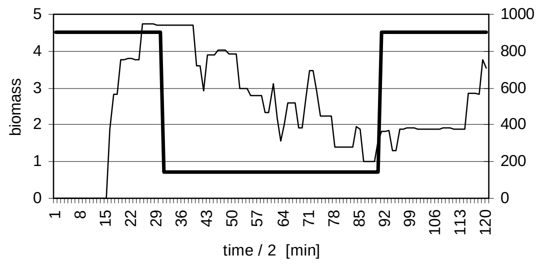

5 robots (nc), run 5, growth 2, average

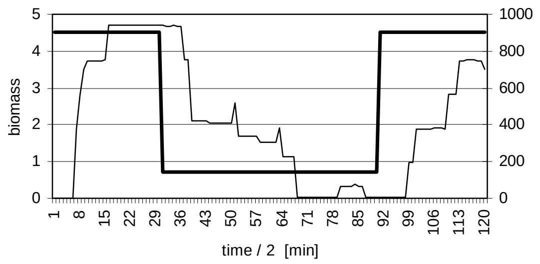

5 robots (nc), run 6, growth 1, average

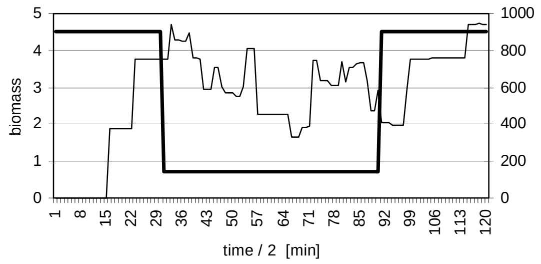

5 robots (nc), run 6, growth 2, average

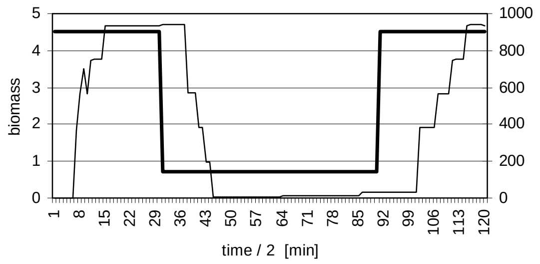

5 robots (nc), run 7, growth 1, average

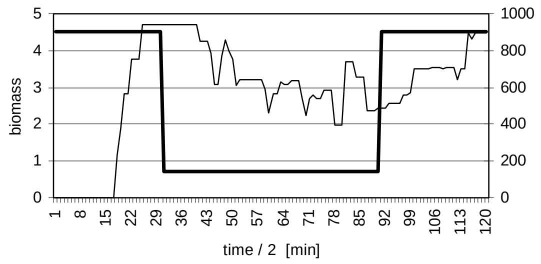

5 robots (nc), run 7, growth 2, average

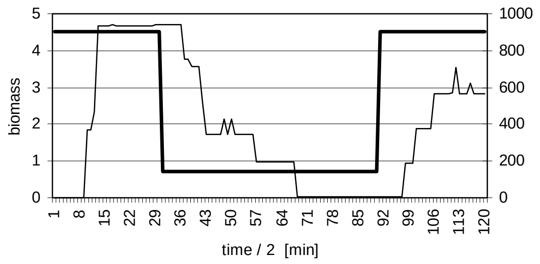

5 robots (nc), run 8, growth 1, average


5 robots (nc), run 8, growth 2, average

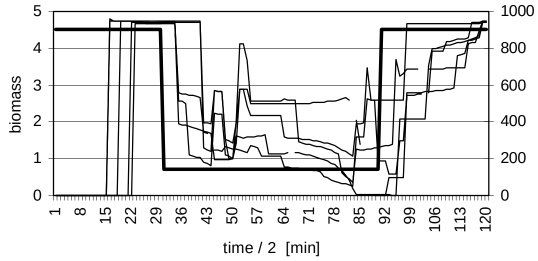

5 robots (nc), run 9, growth 1, average


5 robots (nc), run 9, growth 2, average

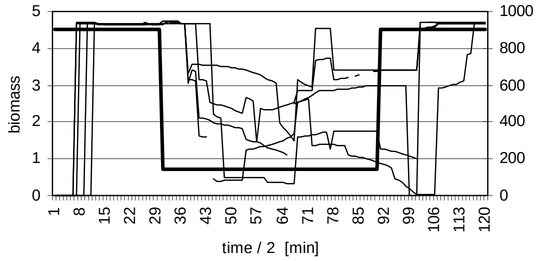

5 robots (nc), run 10, growth 1, average


5 robots (nc), run 10, growth 2, average

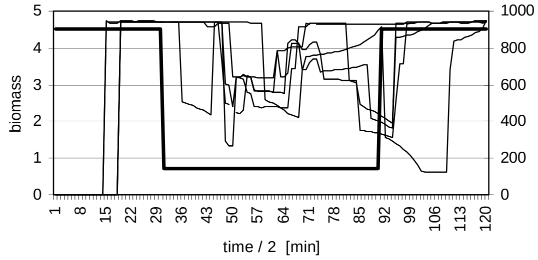
5 robots (cc), run 1, growth 1



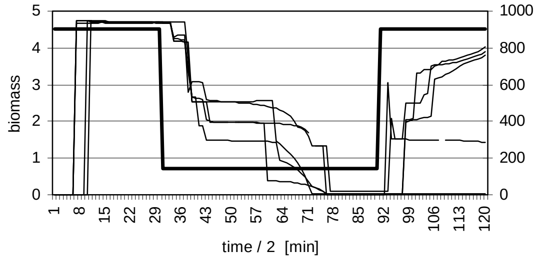
5 robots (cc), run 1, growth 2



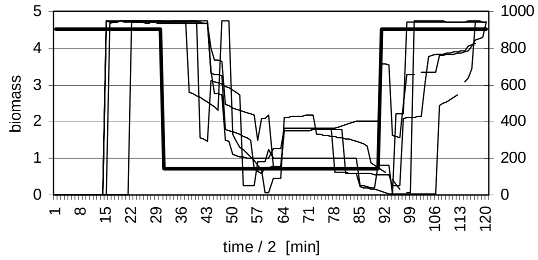
5 robots (cc), run 2, growth 1



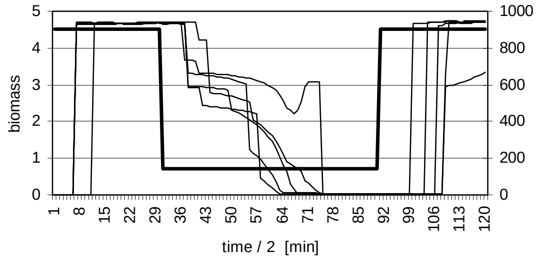
5 robots (cc), run 2, growth 2



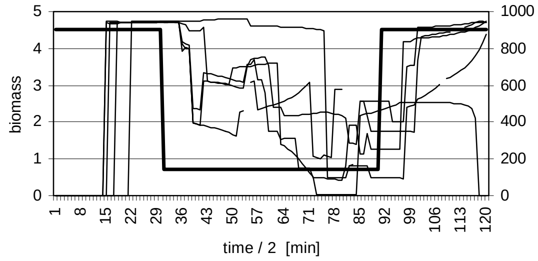
5 robots (cc), run 3, growth 1



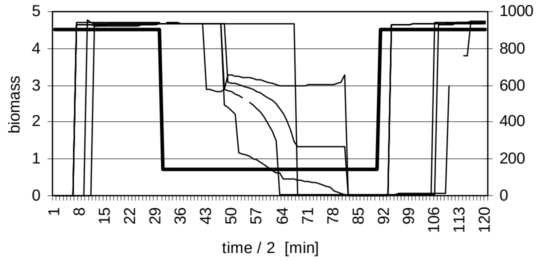
5 robots (cc), run 3, growth 2



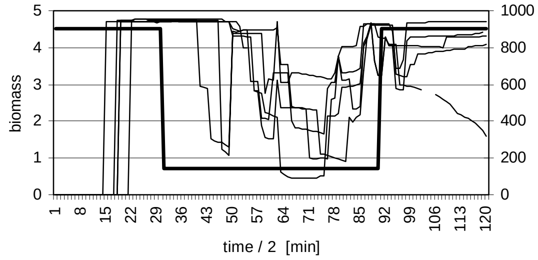
5 robots (cc), run 4, growth 1



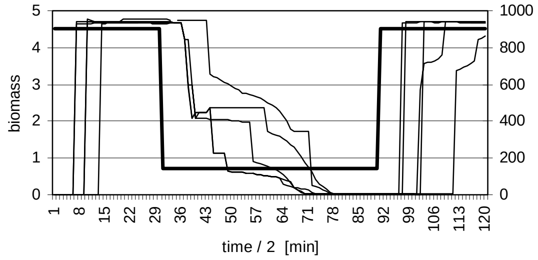
5 robots (cc), run 4, growth 2



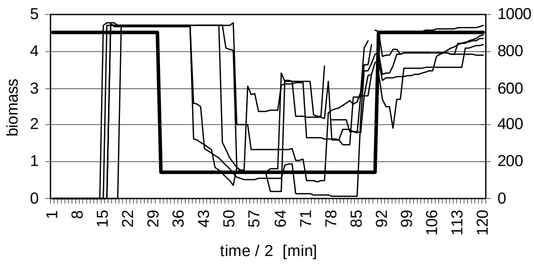
5 robots (cc), run 5, growth 1



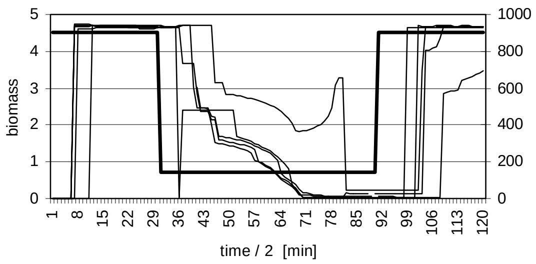
5 robots (cc), run 5, growth 2



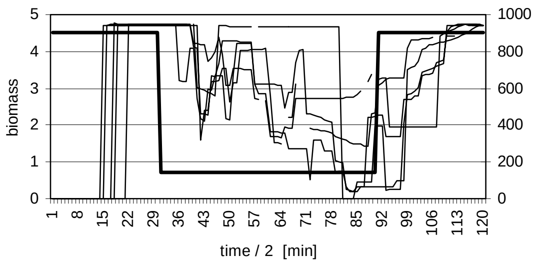
5 robots (cc), run 6, growth 1



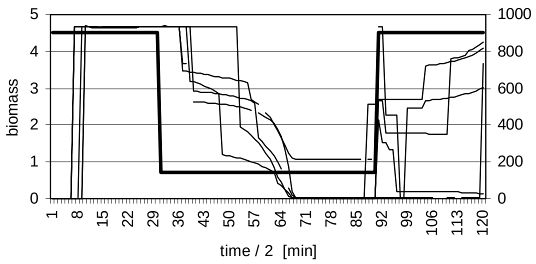
5 robots (cc), run 6, growth 2



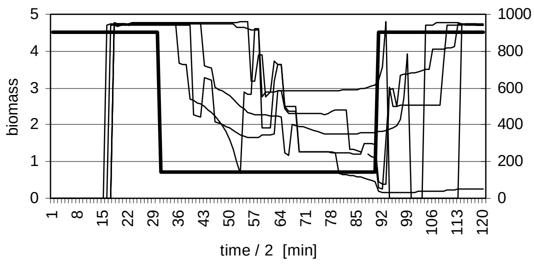
5 robots (cc), run 7, growth 1



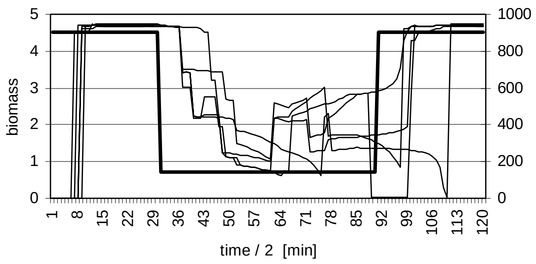
5 robots (cc), run 7, growth 2



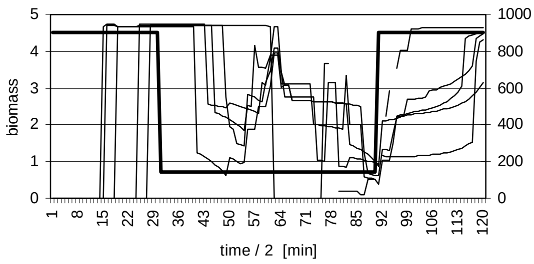
5 robots (cc), run 8, growth 1



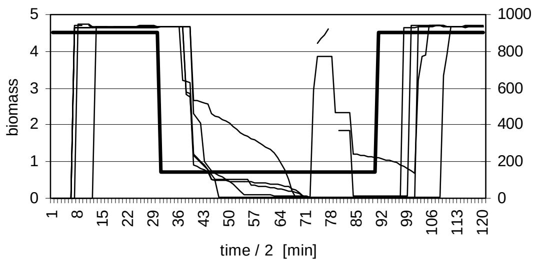
5 robots (cc), run 8, growth 2



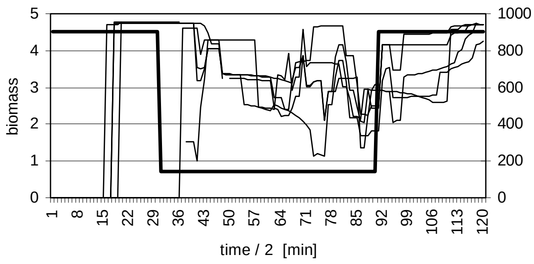
5 robots (cc), run 9, growth 1



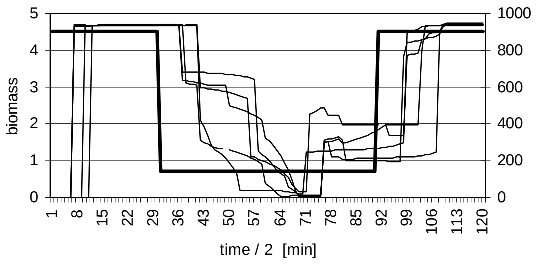
5 robots (cc), run 9, growth 2

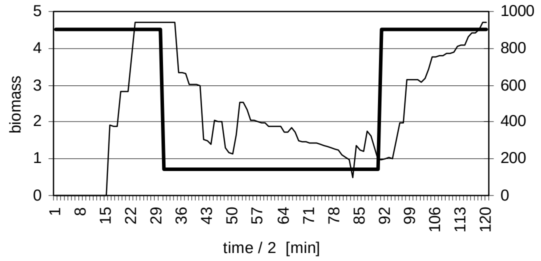


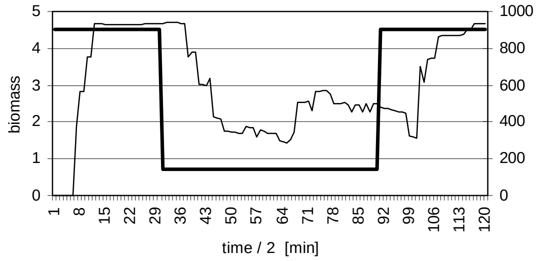
5 robots (cc), run 10, growth 1

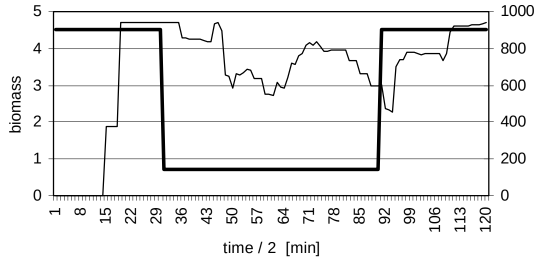


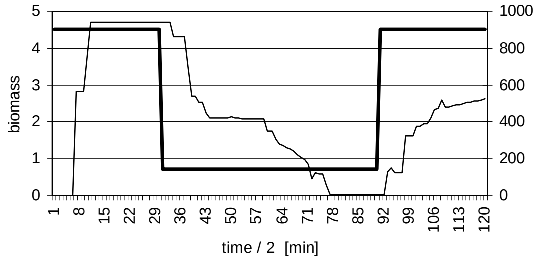
5 robots (cc), run 10, growth 2

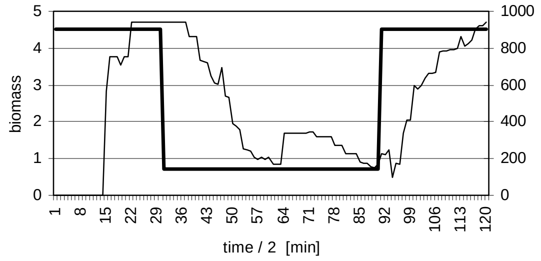


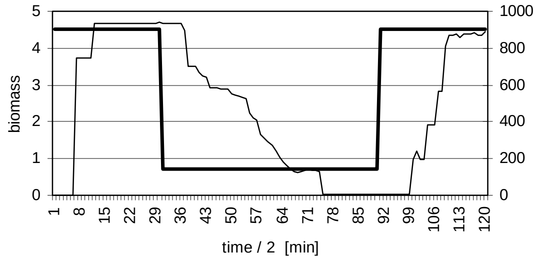

5 robots (cc), run 1, growth 1, average

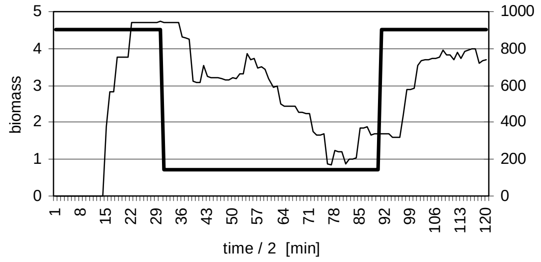

5 robots (cc), run 1, growth 2, average

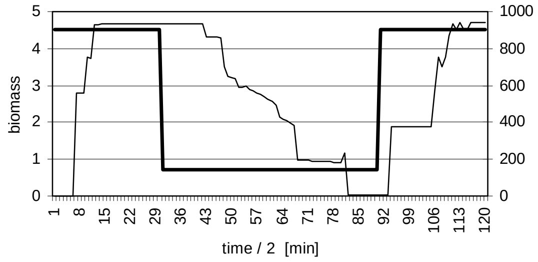

5 robots (cc), run 2, growth 1, average

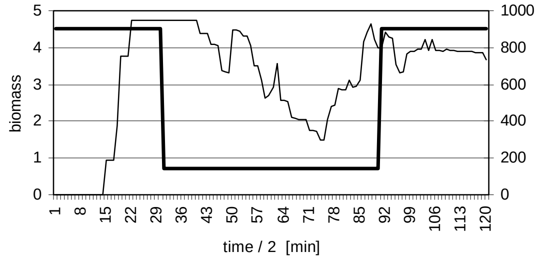

5 robots (cc), run 2, growth 2, average

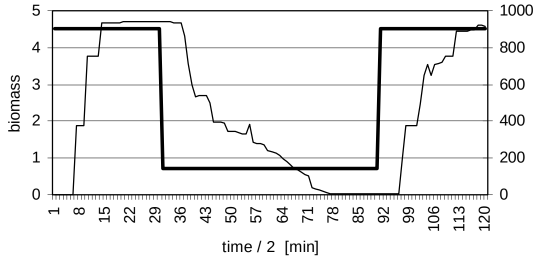

5 robots (cc), run 3, growth 1, average


5 robots (cc), run 3, growth 2, average

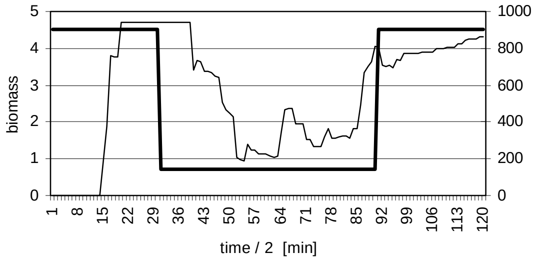

5 robots (cc), run 4, growth 1, average


5 robots (cc), run 4, growth 2, average

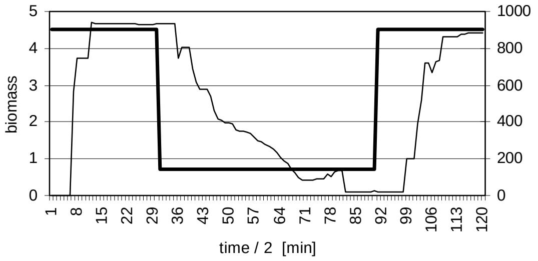

5 robots (cc), run 5, growth 1, average


5 robots (cc), run 5, growth 2, average

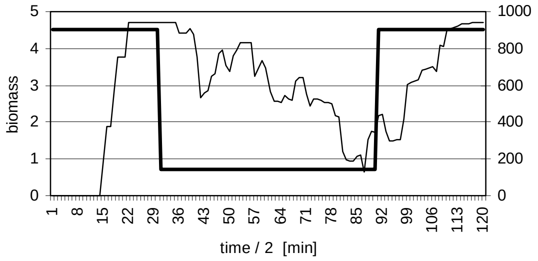
5 robots (cc), run 6, growth 1, average



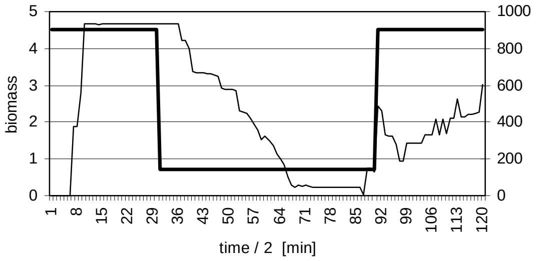
5 robots (cc), run 6, growth 2, average



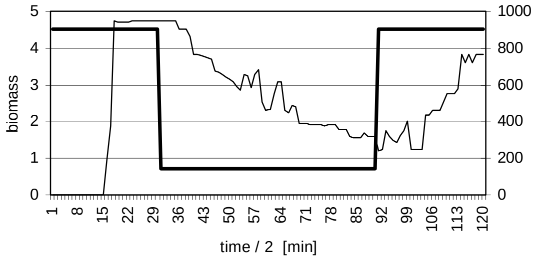
5 robots (cc), run 7, growth 1, average



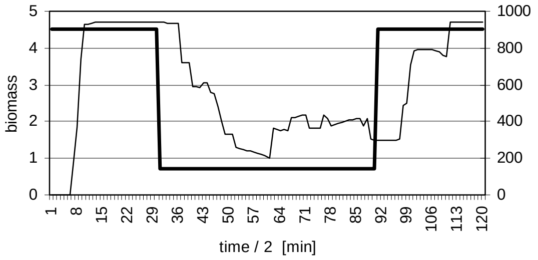
5 robots (cc), run 7, growth 2, average



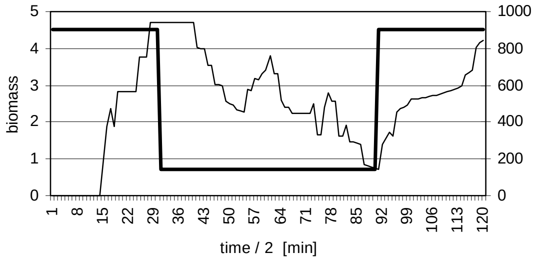
5 robots (cc), run 8, growth 1, average



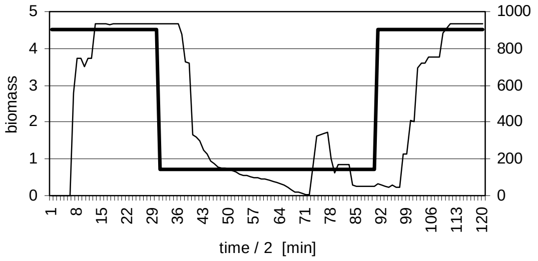
5 robots (cc), run 8, growth 2, average



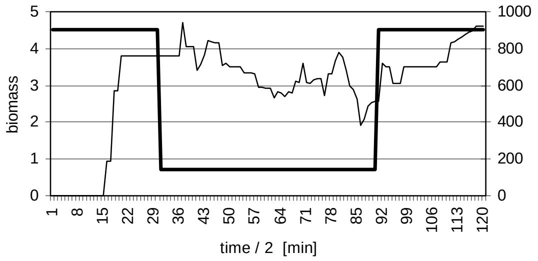
5 robots (cc), run 9, growth 1, average



5 robots (cc), run 9, growth 2, average



5 robots (cc), run 10, growth 1, average



5 robots (cc), run 10, growth 2, average