The I-SWARM Project: Intelligent Small World Autonomous Robots for Micro-manipulation

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Abstract. This paper presents the visions and initial results of the I-SWARM project funded by the European Commission. The goal of the project is to build the first very large-scale artificial swarm (VLSAS) with a swarm size of up to 1,000 micro-robots with a planned size of $2 \times 2 \times 1$ mm^3. First, the motivation for such a swarm is described and then first considerations and issues arising from the robots' size resembling "artificial ants" and the MST approach taken to realize that size are given. The paper will conclude with a list of possible scenarios inspired by biology for such a robot swarm.

1 Vision

In classical micro-robotics, highly integrated and specialized robots have been developed in the past years, which are able to perform micro manipulations controlled by a central high-level control system [1–5]. On the other hand, technology is still far away from the first "artificial ant" which would integrate all capabilities of these simple, yet highly efficient swarm building insects.

This has been the motivation of other research fields focusing on studying such swarm behavior [6] and transferring it to simulation or physical robot agents [7]. Realizations of small robot groups of 10 to 20 robots are capable to mimic some aspects of social insects, however, the employed robots are usually huge compared to their natural counterparts, and very limited in terms of perception, manipulation and co-operation capabilities.

The vision of the I-SWARM project is to take a leap forward in robotics research by combining expertise in micro-robotics, in distributed and adaptive systems as well as in self-organizing biological swarm systems. The project aims at technological advances to facilitate the mass-production of micro-robots, which can then be employed as a "real" swarm consisting of up to 1,000 robot clients. These clients will all be equipped with limited, pre-rational on-board intelligence. The swarm will consist of a huge number of heterogeneous robots, differing in

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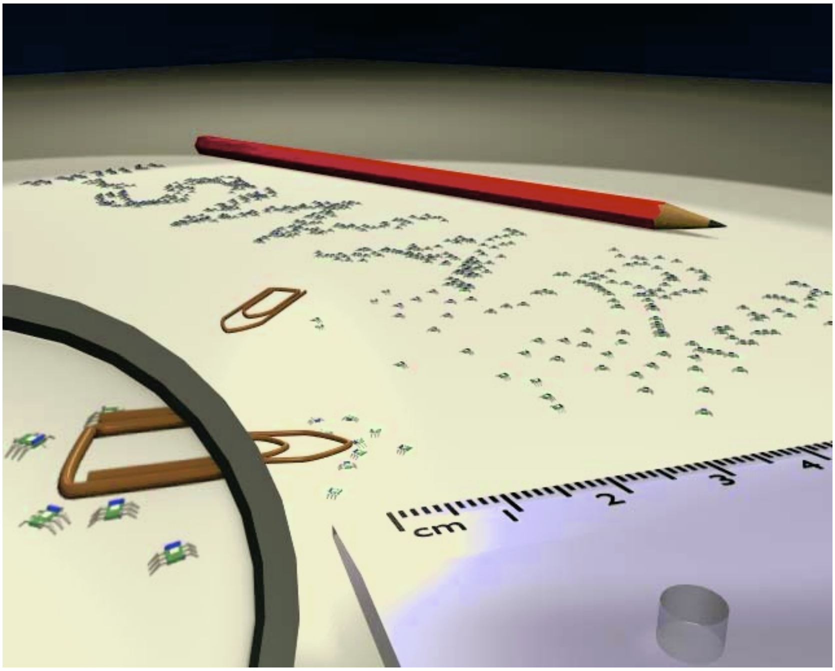

Fig. 1. The I-SWARM: a vision.

the type of sensors, manipulators and computational power. Such a robot swarm can then be employed for a variety of applications, including micro assembly, biological, medical or cleaning tasks.

To realize the project's vision, the consortium has a large expertise in micro-robot technologies. Topics like polymer actuators, collective perception, using (instead of fighting) micro scaling effects, artificial and collective intelligence will be addressed.

The primary goal of the integrated project I-SWARM is the realization of a "real" micro-robot swarm, *i.e.* a thousand micro manufactured autonomous robots will be designed for the collective execution of different tasks in the small world. This will be achieved:

- by the realization of collective intelligence of these robots
  - in terms of cooperation and
  - collective perception
  - using knowledge and methods of pre-rational intelligence, machine learning, swarm theory and classical multi-agent systems.
- by the development of advanced micro-robots hardware
  - being extremely small (planned size of a single robot: $2 \times 2 \times 1$ mm^3.)
  - by integrating novel actuators, miniaturized powering and miniaturized wireless communication
  - with ICs for on-board intelligence and
  - integrating sensors and tools for the manipulation in the small world.

The fundamental vision behind a swarm of micro-robots is the realization of capabilities that are not given by either a single micro-robot, or with a small group of micro-robots. The expected self-organization effects in the robot swarm should be similar to that seen within other ecological systems like ant states, bee colonies and other insect aggregations. The well-known potential benefits of a self-organized system include greater flexibility and adaptability of the system to the environment, robustness to failures, *etc.* Additionally, their collective behavior opens up new application fields, that cannot be solved with today's tools. A suitable sophisticated positioning system will be developed, possibly based on the ones used by insects and incorporating tactile sensors and a small but effective vision system, that will enable the individual agents to communicate between themselves and thus enable and promote the desired swarm effects.

Considering the natural world, it is apparent that insects have been a very successful species during evolution largely due to their ability to organize into large co-operative communities and swarms [8, 9].

A major goal of the project is to transform knowledge gained by observations of eusocial insect behavior, from observations of communicating insect aggregations and research already performed on swarm intelligence of robots and to apply this to a swarm of micro-robots. The micro-robots to be developed within the project will be capable of performing real micro manipulations similar to (some of) the capabilities of insects. In this paper, some of the work carried out within the project will be described, including:

1. Hardware design of a heterogeneous robot swarm: The realization of a large number of robot clients (up to 1,000 or more) will present a major technical challenge and will require new and novel approaches in terms of manufacture and miniaturization. New techniques for the co-design of the miniaturized hardware and its embedded software 'intelligence' will need to be developed.
   (a) In designing the robot hardware, locomotion principles such as insect-like walking will be examined. Research into enhancing this will lead to novel, low-power micro-robot walking mechanisms.
   (b) The knowledge gained by experiments on the "Laws of the small World" will significantly deepen our understanding of microphysics as applied to micro handling.
   (c) The development of pre-rational intelligence modules will help to create a swarm intelligence distributed over the whole system, thus making it less prone to failures and improving its capability to adapt to new situations.
2. More importantly, systems and methodologies will be developed which will enable the swarm's behavior for solving given tasks to be modelled and thus predicted. This will require the development of knowledge not only about the internal systemic behavior of a large number of heterogeneous agents. A major contribution will also be a simulation system which takes into account the hardware capabilities and restrictions of the swarm robots' hardware, *e.g.* sensory capabilities, uncertainties, *etc.* The result of this work will enable the building of customized swarms which will act in a predetermined way.

As a prerequisite of the co-design of the robot hard- and software, swarm scenarios have been identified and classified according to their requirements. A rough categorization of swarm could be the following:

- grouping
- pattern forming or making a queue
- object collection, surface cleaning
- collective perception
- collective transport
- collective sorting and building
- collective maintenance of global homeostasis

There are many applications which can be derived from these scenarios:

- Assembly tasks in the micro world such as assembling of gears, micro pumps and other micro systems,
- Self assembly/self recycling,
- Cleaning surfaces in a very short time,
- Mechanical self configuration,
- Testing and characterization of micro-parts,
- Future medical applications (*e.g.* examine and medicate the human body inside and outside),
- Energy harvesting and distribution within the swarm.

We believe that the availability of a (possibly commercially available) low-cost, mass fabricated swarm micro robot will have a great impact in the fields of education, science and possibly also entertainment.

2 The Micro Robotic Approach

The experience from previous micro-robotic projects shows that we are clearly at the limit of micro-robot development with a modular approach. If we want to develop smaller robots, the design has to change drastically and an integrated approach should be chosen. The selected concepts must allow further miniaturization in the future in order to really reach the micro-scale. The micro-agents' size and force must be in proportion to the size and fragility of the manipulated objects, such as, for instance DNA or living cells. As a large number of micro-agents will have to be realized, batch processes using micro system technology (or MEMS[1]) will be compulsory.

Within this project, robotic agents realized with techniques from micro system technology (MST) and employing insect as well as other motion principles will be investigated. This will allow making the link between two research fields, which do not have much interaction so far. On the one hand, there is a large number of micro-locomotion systems, walkers, conveyors or motors, which have been realized with MST. On the other hand, there is micro-robotics, where certain intelligence is present on autonomous platforms, which are assembled from discrete elements.

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[1] Micro-Electro-Mechanical System.

Actuators based on piezo-optic, thermal or other solid-state effects with the possibility for a direct external energy supply will allow for agents without an energy buffer for locomotion, thus further decreasing the size. The projected size of a robot is $2 \times 2 \times 1$ mm^3 and velocities of up to 1 mm/s. There will be different kinds of micro-agents, each designed for a specific task and each with an integrated nano-tool: optical sensor (1 or a few pixels), needle (*e.g.* functionalized AFM like probe) *etc.* As for the robot itself, a modular approach for the tools is excluded due to the limitations in size.

To create a breakthrough in micro-robot actuation, we are pursuing a bio-inspired approach: in several insects the mechanical structure for locomotion is based on shells and muscles in contrast to *e.g.* bones and muscles in larger animals. A shell structure where bending hinges are used as joints is *e.g.* one way to "mimic" the biological world with artificial structures since most of the micro system techniques allow for planar shell fabrication. Agile limbs and antennas can be made when a suitable "muscle" (actuator) material is integrated with the shell structure. So far most integrated micro-robots have been based on silicon technology. To mimic the biological world, the materials for the backbone of the insect robot could instead be polymeric. Fortunately, there are several micro system technologies for polymeric materials available and the lacking fabrication steps for the actuators will be successively developed. While several of the injection moulding techniques would give large volumes at low prices the most straightforward way of building small microsystems is to use flexible printed circuit boards (FPCB). These boards are extensively used in miniature systems as consumer electronics and high-tech components. The FPCB gives flexibility, electrical connects, three-dimensionality and high-quality material properties. The more expensive FPCB use a polyimide base material that gives high performance and some extraordinary properties. The processing technology will allow for well-defined structures (the shells *etc.* in the insect robot) and well-controlled grooves for the bending hinges. The stiffness can easily be controlled by structural definition (ridges *etc.*) or by metal reinforcement since the main application of the FPCB is as a printed circuit board with metal conductors in top of the carrier.

The actuator development for the integrated robots is performed in several steps. The first evaluation is made with a functional but not optimized muscle material. One example is a thermo-mechanical material that is well compatible with the FPCB processing technology: a photo-patternable polyimide. There are also other interesting actuators that will be considered for the swarm robots. The high power consumption is however the main problem for autonomous operation. One of the more interesting actuator groups are electro-active polymers [10], *e.g.* piezoelectric polymer materials with two main advantages. Firstly, the power consumption should be possible to decrease with two orders of magnitude allowing for long operation times or uninterrupted operation with a continuous power supply. Secondly, the movement stability should be much improved since the actuation is controlled by electric voltage instead of temperature. Particularly the possibility to stop at a given joint angle without any power consumption is important in many of the planned applications. The development of electroactive polymers is rather fast and it can be suspected that some new alternatives will be possible to evaluate soon. At present, modified PVDF types of piezoelectric actuators appear to be the best choice. These materials have a strain and stiffness close to the thermo-mechanical polyimide while the energy consumption per cycle should be two orders of magnitude less. The main challenges with introducing this material in a polymeric micro system are the high electric fields, the electrode materials and the processing techniques.

In the final phase of this project, micro system technologies such as bulk micro machining, piezoelectric thin or thick films, polymer film technologies *etc.* will be employed in the creation of the small mobile micro-robot agents combining features from both the autonomous micro-robots and the MST-based systems.

The functions of the agents will be reduced to locomotion, integrated tool (one per agent) permitting basic manipulation, possibility to attach and release other agents, a limited capability to store information on the state of the agent as well as the possibility to transfer basic information from agent to agent and eventually between agent and a supervisory system / robot.

3 Methodology and Initial Results

Since the project has just started[2], at the time of preparing this paper, no results beyond first hardware tests and initial simulations on the impact of the very limited robot capabilities are yet available. However, the nature of the project has led to very interesting and challenging design issues which will be described in the following along with our approach on how to tackle them.

The fundamental difference in this project as compared to other (swarm) robotics endeavors is that we have not proposed a fixed scenario the final robot swarm is to perform. The proposition, as sketched in Section 1 was rather to realize a swarm consisting of mm-sized robots which should subsequently be programmed and deployed on various scenarios.

This situation is very uncommon in classical engineering, since it implies a co-design of the problem along with the solution, Fig. 2. Since the Consortium comprises partners involved in the design and fabrication of robot hardware and partners involved in software, we initially faced a deadlock situation: Hardware partners requested the required capabilities of the hardware from the software partners, who in turn wanted to know the constraints which will be imposed by the hardware given the stringent limitations in space.

In other words, this project tries not only to explore the space of solutions for swarm robotics as in classical engineering, but also the space of possible problems at the same time. To overcome this deadlock situation, we have started to collect all available data on constraints imposed by physics, available technologies and interactions of subsystems. The resulting analysis is presented in the next two sections. A preliminary list of possible swarm scenarios inspired by biological swarms will conclude this Chapter.

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[2] Project start was in January 2004.

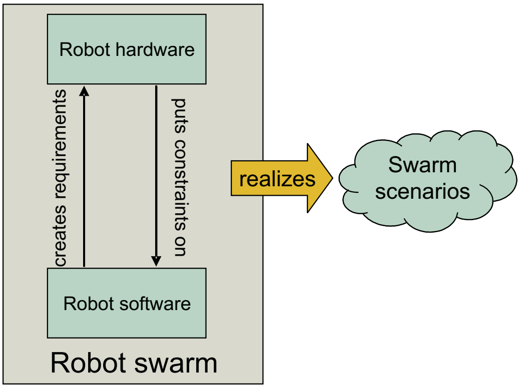

Fig. 2. Unconventional engineering problem in co-design.

3.1 Hardware Constraints

The Consortium is currently investigating principles and techniques for all robot subsystems. Here, the subsystems most crucial for the resulting swarm scenarios will be discussed.

Energy Supply: Speaking of autonomous[3], highly miniaturized robots, the first limitation to be considered is the amount of available on-board energy. If one takes a pessimistic approach, the energy will be limited to 150 μW. One can then further estimate an energy breakdown onto the robots' subsystems: 70% will be consumed by each robot's actuation system, 20% by its hardware circuitry and the rest is available for other functions.

While examining these figures in more detail, it becomes clear that the amount of energy available on the robots is crucial while being a function of the robot's size. For some solutions, it depends only on its surface, for others on the available volume. The list of possible energy sources for an autonomous swarm micro robot is:

- **Batteries**
  - **Non-rechargeable:** commercial types deliver 1 J/mm^3, package sizes are around 30 mm^3 which renders them useless for our case.
  - **Rechargeable:** thick-film batteries deliver 1 J/mm^3, too, and could be used at 0.2 W for about 5,000 seconds (1.4 hours, sufficient for most conceivable scenarios even with very slow robots).
- **Capacitors:** super caps could be operated at 0.2 mW for 1,000 seconds (16 minutes), package sizes are around 65 mm^3.
- **Inductive Energy Transfer:** on-board coils of 2 mm ø could supply 1 mW.
- **Micro Fuel Cells:** size [11, 12] are today still too large for on-board operation and refuelling with methanol will be a major problem given the robots', besides the production of waste water.

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[3] In terms of power supply, and to a large extent of control.

- **Micro Solar Cells:** could deliver between 0.14 mW/mm^2 to 0.35 mW/mm^2 with a light source equivalent to daylight.

The conceivable power supply systems can therefore be classified into continuous and recharging, while the continuous scenario is the more desirable one.

Sensor System: The sensor subsystem of the robots could consist of a tactile sensor principle using a feeler-like design. Principles currently under investigation are piezo- or polymer strips which can operate either passively, or in active modes, by vibration or bringing them to resonance which opens up possibilities to sense the robot's surroundings (approximately one robot's length in distance) or even communicate through this sensor system, too; see Fig. 3. Other principles which will be evaluated are capacitance measurements detecting changes in the dielectric in the robot's surroundings or optical principles.

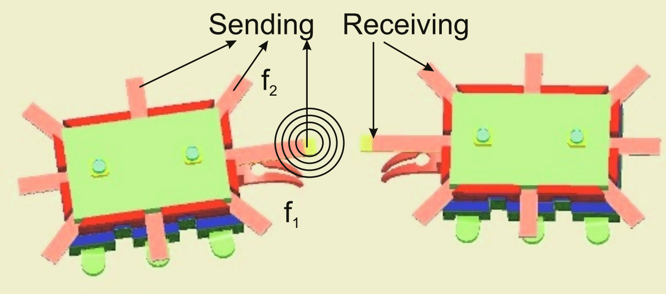

Fig. 3. Communication with a tactile sensor system.

Communication System: The principles which could be employed for robot-to-robot and robot-to-host communication are the following:

- **Classical RF:** commercial solutions like DECT, Bluetooth, WLAN and even ZigBee are not applicable due to the size constraints.
- **Infra-red:** available transceivers have dimensions of 30-40 mm^3. Further problems will be discussed in the next paragraph.
- **Ultra-sound:** sound waves propagating in free air have a very low power efficiency. One alternative would be the transmission of sound through the floor.
- **Inductive:** could be achieved through micro-coils for transmission distances below 2 cm.

Considering these observations, robot-to-host communication will have to be performed using a hierarchical approach: propagating gathered data to (a few) higher-level robots with more advanced communication and sensing abilities which will then send the data to a host.

For optical sensor or communication principles, the restrictions of the available energy are the most striking: standard infrared light diodes require between 50 and 150 μW. This would mean that optical communication and actuation are mutually exclusive (or impossible at all in the worst case, since no power for the circuitry and other functions would be available when light is being emitted).

Since the radiation characteristics of standard diodes produce their maximum output upwards, robot-to-robot communication by optical means will require extra integration work to emit light in the robots' plane. Additional problems arise from technological restrictions[4]: processes which could be used to fabricate the robots' hybrid D/A circuitry rise compatibility issues with processes necessary to structure light emitting diodes. One possible solution (as employed in the Smart-Dust project) would be the use of an external light source and robot-mounted micro-mirrors (or shutters) which can be actuated to avoid the necessity of on-board light generation.

Summary: As a result of this first design phase, a document has been created which lists all necessary robot subsystems along with their characteristics regarding size, die-area, power consumption and compatibility with different manufacturing processes.

An additional task within the project deals with micro scaling effects. These effects occur when scaling an object, *e.g.* a cube with side length a to 1 mm and below: the gravitational decreases with a^3, while surface forces (adhesion due to humidity, electrostatic forces or molecular forces like Van-der-Waals forces) decrease only with a^2. For objects below 1 mm, surface forces start to dominate the volume forces. Based on simulation results of such forces, we expect to be able to use such forces in micro robotics for actuation and manipulation instead of avoiding them.

3.2 Software Considerations

To work towards possible swarm scenarios not only from the hardware side (which could result in a highly miniaturized robot which has too limited capabilities for even the most basic emergence effects to occur), we are also approaching possible scenarios from the simulation and robot design side.

For this, we have derived a morphological table of possible swarm scenarios as outlined in the next section (3.3) and added the requirements on the robot hardware to each scenario. To complement this analysis, we have also started simulations to assess the impact of the availability and performance of different robot subsystems (*i.e.* sensors, locomotion system *etc.*).

The considerations on the hardware and software side are now being iterated in order to gain a deeper understanding of the restrictions which have to be considered. Additionally, this process also yields new scenarios which have not been thought of before. One example is a non-continuous power supply scenario (*i.e.* the robots have rechargeable energy supplies on board), where robots are "rewarded" for achieving a task by energy. This could for example be a collection task where robots which deliver a workpiece will be "refuelled", while robots performing this task badly will eventually "die" due to a lack of energy.

3.3 Scenarios

In the following paragraphs, initial ideas inspired by biological counterparts [16] are presented. This description is still quite vanilla, since we are currently eval-

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[4] Since the robot size will limit the electronics to basically a single chip.

uating the suitability and feasibility of the scenarios for a robotic swarm. Some initial hints on the realization are given below, but for each scenario, there are many ways to imitate the concepts that biological swarms use (for example, virtual pheromone [17]: this can be simulated by a projected light gradient [18], or by robot-to-robot communication, or other sensor principles).

Scenario 1: Aggregation: This scenario represents a simple aggregation of the robots in a self-organized manner. This behavior is inspired by slime molds or by cockroaches. The robots have the goal of positioning themselves into a larger group.

Scenario 2: Aggregation Controlled by an Environmental Template: In this scenario, the robots have to aggregate in the arena, too. In contrast to Scenario 1, an environmental template influences this aggregation. The environmental template could be a light source which has another color than the one used for a "virtual pheromone". The goal of this scenario is that the robots must aggregate as near as possible to the center of this template. This phenomenon can be found in nature by slime molds and cockroaches, too.

Scenario 3: Collective Building of Piles: The "Collective Building of Piles" scenario is one of the most researched scenarios in the AI community. The goal of the robots is to collect pucks, which are initially randomly distributed over the whole arena, and build up one ore more piles. This scenario is a good base for studying more advanced scenarios like the following one.

Scenario 4: Collective Sorting: This scenario is a more advanced version of the latter one. It involves a controlled environment with different regions within the arena. Those regions could be distinguished by the robots, for instance through different light intensities or colors, which are projected with a high-resolution beamer from the top of arena. Additionally, there are several sorts of pucks which differ in a feature that is recognizable by the robot. The goal of the robot is to bring a puck to the region of the arena which corresponds with the type of the puck. This behavior should lead to a guided sorting of the pucks within special regions. Ants use such mechanisms to sort their brood according to the ambient soil temperature and humidity. Depending on the robots' capabilities, the projected gradient could also be replaced by (local) broadcasts depending on the robots' communication capabilities.

At the first glance this scenario seems quite easy, but distinguishing between different objects is a very difficult task for micro-scale robots.

Scenario 5: Royal Chamber: The "Royal Chamber" scenario goes back to investigations on the ant species *Leptothorax albipennis* that build a wall around their queen. The distance of this wall is affected by a pheromone that is excreted by the queen. As in nature, the robots should collect building-material (pucks) and dispose it around an imaginary queen. The queen's pheromone is represented by a potential field that can be, as in the latter scenario, projected on the arena.

The robots should deposit the pucks at a given potential to form the royal chamber. If the potential field changes – the queen grows – the robots should reconfigure the built wall.

Scenario 6: A Court Around a "Robot Queen": In this scenario, we have two types of robots: the "queen robot" which is bigger in size and moves slowly in the arena, and the "worker robots". The "queen robot" emits a "virtual pheromone" that affects the random walk of the workers. They are directed uphill the pheromone gradient until they reach the queen. Then the worker robots join the court of the queen. By the time they are exposed to the pheromone, their reaction threshold increases. This effect will cause the robots to leave the court, at least when the queen is moving. The goals of this scenario are to have a maximum filled court of the queen and at the same time distribute the non-court robots uniformly in the arena.

This scenario is inspired by the honeybee queen court. In the case of the honeybee queen, the formation of the court as well as the joining frequency per bee seems to be affected by the moving speed and turning frequency of the queen. The moving activity of the honeybee queen is often associated with her egg laying, which then results in different egg laying patterns.

Scenario 7: Collective Foraging Using Bucket Brigades: In this scenario, the robots collectively forage a food from a known place and untread to the known nest. In this scenario we have only 3 distinct groups of robots: the "big", the "median" and the "small" robots which differ by their size and their speed. Every time a bigger robot has contact with a loaded smaller robot, the smaller, but faster robots drop the object and turn again towards to the food source. The bigger and slower robot lifts the object, turns and transports it towards to the nest. This behavior is inspired by ants. The common goal of the swarm behavior is to collectively maximize the number of transported objects per time unit.

Scenario 8: Collective Foraging for Objects Using Pheromone Trails: A group of robots in this scenario collectively chooses the optimal source by assessing the distance from the "nest" to the source. A "virtual pheromone" deposited on the best source by the robots can be detected by other foraging robots. Then several robots go to this source. A goal of this scenario is to collect an objects from several food sources by minimizing the time spent outside of the nest.

Scenario 9: Foraging with Distinction of the Source Quality: As in the last scenario, the robots should forage by building a "virtual" pheromone trail. In this case, however, they distinguish between the food sources and deposit more pheromone for a better source. This scenario builds also on the "Collective Sorting" scenario. The robots must recognize the different food sources and evaluate them. There are two possibilities for evaluating the food sources. The easiest one is that they know the value of the source after they identified it. The other one, and the harder one, would be that the robots are rewarded by an intelligent arena after delivering the food.

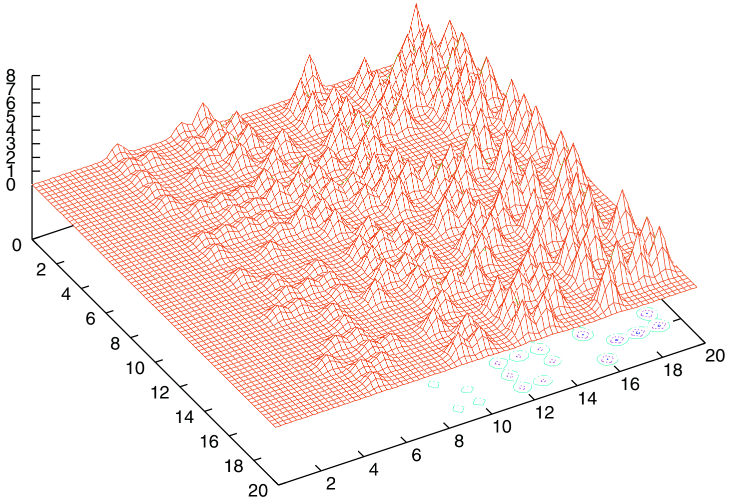

Fig. 4. Pheromone map for the nursing task.

Scenario 10: Dynamic Task Allocation: This scenario should model the process of brood nursing in social insects. There are two kinds of robots and two kinds of “virtual” pheromones. The two pheromones represent two different kinds of larvae. If a larva was not fed for a given time it starts secreting pheromone. This pheromone is spatially very strictly bounded, see Figure 4. Each kind of robot is more attracted to one kind of “virtual” pheromone. If a robot stays at the peak of a pheromone, the pheromone level there will decrease – the robot is feeding the larvae.

The goal is to keep the brood on an equal pheromone level even if the number of robots of the one kind is decreased (deactivated). The other robots should then take over their part. This should lead to a dynamic task allocation within the swarm.

3.4 Conclusions

The list of scenarios in the last section is currently far from being complete. It will also certainly comprise of scenarios which are plainly impossible for robots of the planned size (and even for much bigger ones). However, it currently serves us as a starting point for the assessment of a minimal robot configuration which is necessary for the I-Swarm to be of any scientific interest. Based on this list, a morphological table of possible swarm scenarios has been created in a spreadsheet which serves as a means of exploring the parameter space of all possible robot subsystem configurations and the impact on the possible scenarios.

One of the possible results of this initial design phase could clearly be that the planned size of $2 \times 2 \times 1$ mm^3 is not feasible since it will make the possible swarm scenarios too simple to be of any use. However, the design decisions taken could be re-used for later projects when more advanced micro techniques are available.

4 Discussion and Outlook

This paper presented a new challenging project, that will push the swarm and micro robotics to a new frontier. Currently, the project is in the starting phase. As described in Sections 1 and 2, several new techniques are being evaluated regarding new algorithms in swarm intelligence, collective perception and MST. As outlined in Section 3, a novel approach to building not only a swarm of robots, but also exploring the space of possible swarm scenarios as a function of the robots' capabilities has been taken. Being able to implement and test swarm algorithms with a VLSAS will lead to a new understanding of eusocial insects and swarm robotics.

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References

1. Seyfried, J.; Fatikow, S.; Fahlbusch, S.; Buerkle, A.; Schmoeckel, F.: Manipulating in the Micro World: Mobile Micro Robots and their Applications Int. Symposium on Robotics (ISR), Montreal, Canada, May 14–17, 2000
2. A. Almansa-Martin: "Micro and nanorobotics – present and future". In Proc. of the 35th International Symposium on Robotics, Paris, March 23–26 2004
3. Martel, Sylvain et al.: "Three-Legged Wireless Miniature Robots for Mass-Scale Operations at the Sub-Atomic Scale", Proc. 2001 IEEE Int. Conf. Robotics & Automation, ICRA 2001, Seoul, Korea, May 21–26, 2001, pp. 3423–3428
4. K. S. J. Pister, J. M. Kahn and B. E. Boser, "Smart Dust: Wireless Networks of Millimeter-Scale Sensor Nodes", Highlight Article in 1999 Electronics Research Laboratory Research Summary
5. S. Hollar, A. Flynn, C. Bellew, K.S.J. Pister, "Solar Powered 10 mg Silicon Robot," MEMS 2003, Kyoto, Japan, January 19–23, 2003
6. Eric Bonabeau, Marco Dorigo, Guy Theraulaz. Swarm Intelligence: From Natural to Artificial Systems. Oxford University Press 1999.
7. C. R. Kube, H. Zhang, "Collective Robotics: From Social Insects to Robots". Adaptive Behaviour, 1993, Vol. 2, No. 2, pp. 189–218.
8. Self-Organization in biological systems. S. Camazine, J.-L.Deneubourg, N.R. Franks, J. Sneyd, G. Theraulaz, E. Bonabeau. Princeton University Press (2001).
9. A.E. Hirsh, D.M. Gordon. Distributed problem solving in social insects. Annals of Mathematics and Artificial Intelligence 31, pp. 199–221 (2001).
10. Y. Bar-Cohen (Book Editor and author/co-author of 5 chapters), "Electroactive Polymer (EAP) Actuators as Artificial Muscles – Reality, Potential and Challenges", ISBN 0-8194-4054-X, SPIE Press, Vol. PM98, (March 2001), 671 pages.
11. Ieropoulos, I., Greenman, J., Melhuish, C. (2003): "Imitating Metabolism: Energy Autonomy in Biologically Inspired Robotics", in Proceedings of the AISB 03, Second International Symposium on Imitation in Animals and Artifacts, SSAISB, Aberystwyth, Wales, pp. 191–4.

12. Chris Melhuish, John Greenman, Kevin Bartholomew, Ioannis Ieropoulos and Ian Horsfield. “Towards Robot Energetic Autonomy using Microbial Fuel Cells”, (in press) J. Electrochimica Acta (special edition).
13. Woern, H.; Seyfried, J.; Fahlbusch, St.; Buerkle, A.; Schmoeckel, F.: Flexible Microrobots for Micro Assembly Tasks International Symposium on Micromechatronics and Human Science (HMS 2000), Nagoya, Japan, October 22–25, 2000
14. Woern, Heinz; Schmoeckel, Ferdinand; Buerkle, Axel; Samitier, Josep; Puig-Vidal, Manel; Johansson, Stefan; Simu, Urban; Meyer, Jörg-Uwe; Biehl, Margit From decimeter- to centimeter-sized mobile microrobots – the development of the MINIMAN system SPIE’s Int. Symp. on Intelligent Systems and Advanced Manufacturing, Conference on Microrobotics and Microassembly Boston, MA, USA, October 28–November 2, 2001
15. Buerkle, Axel; Schmoeckel, Ferdinand; Kiefer, Matthias; Amavasai, Bala P.; Caparrelli, Fabio; Selvan, Arul N.; Travis, Jon R.: Vision-based closed-loop control of mobile microrobots for micro handling tasks SPIE’s Int. Symp. on Intelligent Systems and Advanced Manufacturing, Conference on Microrobotics and Microassembly Boston, MA, USA, October 28–November 2, 2001, pp. pp. 187–198
16. Schmickl, Thomas: Scenarios for the robot swarm. Internal Report of I-Swarm Project. May 2004. University of Graz, Austria, IZG.
17. Payton, D.; Daily, M.; Estowski, R. et al.: “Pheromone Robotics” in Autonomous Robots vol. 11, pp. 319–324, 2001
18. Kazama, T; Sugawara, K; Watanabe, T.: “Collecting Behavior of Interacting Robots with Virtual Phero-mone” in Proc. of the 7th International Symposium on Distributed Autonomous Robotic Systems (DARS 2004), June 23–25, Toulouse, France, pp. 331–340