2005 IEEE/RSJ International Conference on Intelligent Robots and Systems

Minimalistic approach towards communication and perception in microrobotic swarms

S. Kornienko, O. Kornienko, P. Levi
Institute of Parallel and Distributed Systems, University of Stuttgart,
Universitätsstr. 38, D-70569 Stuttgart, Germany

Abstract— **This work is primarily devoted to specific communication and sensing approaches applied for large microrobotic swarms. We investigate the minimal capabilities of a microrobot which still enable the whole robotic group to perform collective activities. These minimal capabilities are implemented in the hardware which allows exploring a phenomenon of swarm intelligence in real experiments. The components of the developed system consume energy provided by microcontroller's I/O ports, are cheap and available on micro-component market.**

Index Terms— **Microrobotics, Microrobotic Swarm, Perception, Communication in Swarm, Swarm Intelligence**

I. INTRODUCTION

Miniaturization of systems and devices represents in the last time an important trend in many areas of science [1]. The current miniaturization achievements in robotics goes to 1 mm^3 robot, as demonstrated in the I-Swarm project [4]. Such a miniaturization opens new challenges not only in mobile robotics but also in many connected areas such as sensor systems, locomotion, energy supplying and so on. Especial attention is attracted to collective capabilities of multi-robotic systems, known as collective/swarm intelligence (collective AI) [2].

Actually, the most exiting questions appear in the area of collective capabilities of a microrobotic swarm [7]. The point is that almost all computational, communication and sensing capabilities of robots are scaled down at a miniaturization. The tasks, arisen in applications, cannot be accomplished individually, like in "normal-scale" robotics. Even such "simple activity" as a navigation requires collective effort of the whole group. Thus, the main point in a swarm robotics is shifted from the *individual intelligence* of a single robot to *collective intelligence* of microrobotic group. Here we encounter many following questions: *"Which minimal degree of "individual intelligence" does allow an emergence of "collective intelligence" ?"*, *"How to achieve this collective intelligence ?"* and so on.

In the "collective" scientific community these points are widely discussed [6], [10]. In a current understanding, the local communication and individual perception are expected to be central to appearance of collective/swarm intelligence. However the main problem here is that a miniaturization extremely limits these capabilities of a robot. The hardware and software solutions, well-known in "normal-scale" robotics, are hardly applicable here. To develop and to test new principles of communication and individual perception in microrobotic swarms, we need, among other, the test platform. This test platform should be cheap, easy to assemble, however possesses such capabilities that enable growing collective intelligence. In this paper we demonstrate the development of communication, proximity sensing (for navigation) and perception (for object recognition) system for a test microrobot. The size of the test platform is 23×23×28mm, it uses the Megabitty board with Atmel AVR Mega 8 microcontroller [11].

During this development we encountered several essential problems in communication and perception. The main problem of a swarm-based communication consists in propagating information through a swarm. Firstly, capabilities of a microrobot are too limited to route the messages. Secondly, it is very important for robots to know not only the content of messages ("robot X found resource Y") but also their context ("where Y is found"). In this and other papers (e.g. [8]) we demonstrate principal character of this problem and suggest the hardware and software solutions.

The main problem of sensing consists in a nonlinearity of "micro-perception". The point is that only the IR solution satisfies application's requirements and is feasible in the microrobot. The IR based perception is highly nonlinear in many aspects. In the paper we briefly describe the hardware and software solutions absorbing these nonlinearities and allowing proximity sensing and recognition of surfaces geometries. In the development the especial care is taken about energy consumption, size and availability of components.

The rest of the paper is organized as follows. In Section II we formalize and formulate requirements imposed on communication and perception. Section III is devoted for implementation of these requirements in hardware. Software part is described in Section IV. Finally, in Conclusion we summarize the main results.

II. REQUIREMENTS IMPOSED ON COMMUNICATION AND SENSING IN REAL SWARM

One of our goals is to create a simple microrobot, that could be easy reproduced without special equipment. Therefore, the communication and sensing components should be cheap and available on micro-components market. They should consume as less energy as possible so that to be directly powered by I/O port of microcontrollers, as such from Microchip or Atmel (20-25 mA each port, totally up to 300-400 mA). They

---

*This work is partially supported by the I-Swarm project [4].

should be also of a small size so that to be placed in the chassis of 23x23x28mm. Finally, the same sensors have to be used, as far as possible, for communication, proximity sensing and perception. We consider primarily radio-frequency (RF), wire (WR) and infrared (IR) solutions for communication. For sensing we can use many different sensors, however they have to provide appropriate information for further collective perception.

The *RF* provides duplex communication within several meters and modern one-chip RF modules, even 802.11b/802.11g modules, consume energy in mW area. However we have a serious objection against RF in a swarm. Firstly, simultaneous transmissions of many (80-150) microrobots lead to massive RF-interferences. Secondly, RF-systems with a large communication radius transmit local information (exchange between neighbor robots) globally in a swarm. This local information does not have too much sense for all robots, so that we have high communication overhead in this case. RF-communication is still useful for a global host-robot communication.

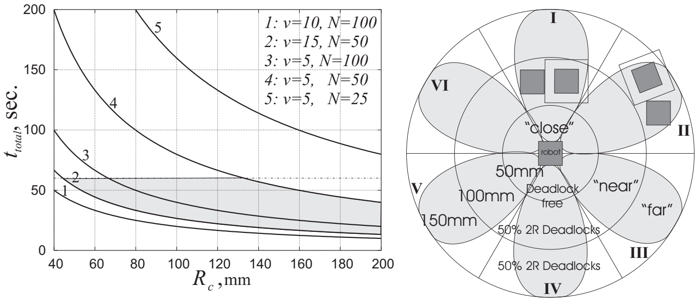
Wire communication takes place when one robot touches another one. In this moment they have high-speed connection, where essential amount of information can be exchanged within milliseconds. Although transmission speed is high, the communication radius is of robot's body (20-30 mm), therefore the time required for global propagation of information is very large.

The *IR communication* is recently dominant in so-called small-distance-domain, as e.g. for communication between laptops, hand-held devices, remote control and others. In IR domain we can choose between several different technologies, like IrDA[1], 34-38 Khz PCM-based devices and so on. Additional advantage of IR solution consists in performing communication and proximity/distance sensing with the same sensors. IR emitter-receiver provides half-duplex communication, they are compact and energy consumption corresponds to I/O ports of microcontrollers. The IR solution is not new in robotic domain, see e.g. [9], [12], however there are almost no solutions that combine perception, proximity sensing and communication.

Although the IR can be used for *sensing*, a small LCD camera (or faceted camera) is also feasible and could be also very useful for a microrobot. We tested some low-resolution (10×10-20×20 pixel, omnidirectional and directional) images for navigation and perception. Based on region and edge extraction approaches, they can be applied for object detection, however we have serious problems with collective perception in this case. The geometry of surfaces, scanned by IR beam, provides much more information for collective perception, than edges and regions from grey-scale images. Taking into account the functionality, energy consumption, size and price of all solutions, we decided to use only IR both for communication and proximity/distance sensing.

A. Requirements imposed on swarm communication

The first requirement concerns the communication radius R_c. For collective systems a communication plays a role of nervous system in human body. Since microrobots in a swarms can communicate only locally, such a "swarm nervous system" can be produced only by a mechanism that propagates information through multiple robot-robot connections. Parameters of a global circulation of information (like global propagation speed or global propagation time t_{total}) depends on characteristics of local communication (communication radius R_c, number of robots within R_c). In the work [8] we investigated this relation and came at the conclusion that for the swarm area $1000 \times 1000\ mm^2$ with $N = 50$ robots the R_c lies between 50mm and 140mm. This guarantees the average propagation time 60 sec. In Fig. 1(a) we plot t_{total} depending of R_c with different values of N and motion velocity v.



(a) (b)

Fig. 1. *Global propagation time t_{total} as a function of communication distance R_c with different values of velocity v and the number of robots N. Area available for the swarm is* $1000 \times 1000\ mm^2$.

Secondly, a communication in a swarm should be directional. The point is that a robot has to know not only a message itself, but also a spatial context of this message (e.g. the direction from which the message is received). The swarm intelligence is primarily based on a capability of communication to provide the context of messages. The number of directional communication channels is also closely related with the problem of IR interferences (Fig. 1(b)). They appear, like in RF case, when several robots start a transmission simultaneously. The implemented in 802.11x logical scheme "Carrier recognition" cannot be implemented here because of a specificity of IR radiation (two not modulated IR signals are simply added) and limited computational capabilities of microcontrollers.

The problem of IR interferences can be avoided by restricting the opening angle of a pair IR receiver-transmitter. For four communication channels, opening angle of each channel is 90^o. In this case we have 2-robots and 3-robots IR interferences even in the "closest" radius (50 mm). Reducing the opening angle to 60^o or to 40^o allows avoiding IR interferences in the "close" and "near" radius (100 mm). Since many microcontrollers have usually 8 ADC (one ADC input is used by the distance sensor), we choose 6-channel directional communication.

---

[1] IrDA requires additional chips, and if we think about 4-6 channels communication, this solution is not really suitable for the implementation in microrobots.

We also expect that robots possess some sensor with PCM-filter for receiving a global modulated signal. Such a signal can be thought as of a remote control or a global information exchange between robots.

B. Sensing

We expect to have proximity sensors in each of motion directions, that can estimate a distance to an obstacle as "far", "near" and "close" (Fig. 1(b)). In the most scenarios imposed on a microrobotic swarm, robots have to perform different spatial operation, like building spatial formation, recognition of object's size and so on. For these tasks robots need a sensor that can measure the distance between itself and an obstacle. Measuring distances, geometrical features and visible size of surfaces are expected to be obtained. Based on them the robot can perform first the individual surface recognition, that can later be expanded on collective perception of large objects.

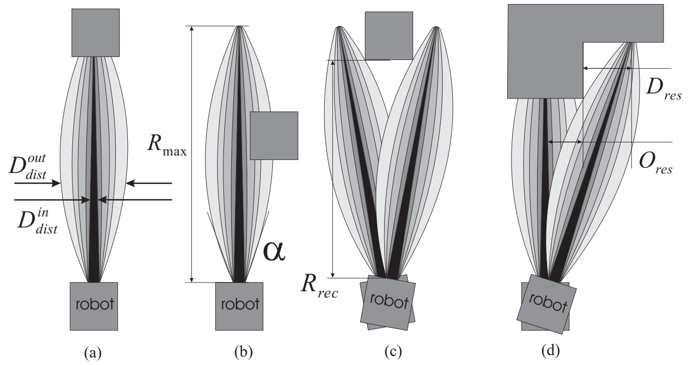


Fig. 2. *Perception of geometries by IR beam.* **(a),(b)** *Example of indiscernible distance;* **(c)** *Active perception of the robot;* **(d)** *Recognition of geometries.*

In the distance measurement the following parameters are the most important: max. measuring distance R_{max}, optimal recognition distance R_{rec}, opening angle of radiation/reflection ray α on R_{rec}, degradation of the IR radiation outsize opening angle $D_{dist}^{in}/D_{dist}^{out}$, object and geometry resolution O_{res}, D_{res} in R_{rec}, dependency of reflection on color/slope of an object, as shown in Fig. 2. We expect that distances are provided, at least, within R_c and a section of the IR radiation cone is less than the size of robot's body.

IR device	**Number**	**Opening angle**	**Reflection/ communic. distance**
Proximity sensors	min. 4, max. 6	90-60	"large" 100-150 mm "near" 50-100 mm "close" 0-50 mm
Distance sensor	1	10-15	max. 150mm
Touch sensor	1	10-15	0mm(touch)
Color sensor	1	—	—
Communication transmitter-receiver	6-8	60-40	max. 140 mm
PCM-receiver	1(compos. 3)	90-120	max. 1000 mm
PCM-emitter	1(compos. 3)	90-120	max. 1000 mm

TABLE I

Required IR devices for a micro-robot.

The general problem of distance and proximity sensing is so-called indiscernible distance (Fig. 2(a,b)). The sensor cannot differentiate whether the object is on the central line but in a large distance, or the real distance is smaller but the object is displaced from the central line. This problem still remains open (can be solve when a robot undertakes several measurements in different directions).

Finally, robots should have some touch sensor, that is required for transporting operations. Sensors, that can perceive a color of objects, are also useful in many scenarios. We collect the required IR devices in Table I.

C. Influence of ambient light on communication/reflextion

Ambient light represents generally very critical issue, because it can essentially distort or even completely break IR communication/sensing. The experiments are performed with luminescent lamp, filament lamp and daylight. We can estimate three different components of a distortion introduced by ambient light. The direct light saturates photoelectric transistor so that it gets "blind". Secondly, ambient light reduces sensor sensitivity, even when it does not fail directly on sensor. Finally, indirect ambient light reduces contrasts between object and background, so that results of measurement are no more reliable and reproducible. In Table II we collect some qualitative results. As followed from this table, a **swarm has to be protected against a light of filament lamps. As far as possible, the direct daylight should be also avoided.** Use of modulated light can essentially improve communication against ambient light, however this solution is not always feasible/acceptable.

IR device	**Filament lamp**	**Daylight**	**Luminescent lamp**
IR sensors without ambient light filter $\lambda \approx$ 300...1100 nm	completely "blind"	"blind" or sensitivity very reduced	R_c reduced on 20%-50%
IR sensors with ambient light filter $\lambda \approx$ 880...1000 nm	R_c reduced on 80%-90%	R_c reduced on 20%-50%	small "dark" current
IR sensors based on modulated IR radiation	it works, but not always stable	OK for small R_c, not stable for large R_c	no remarkable enfluence

TABLE II

Some qualitative results by testing different IR devices with ambient light.

The filament lamps can be used as a global pheromone to control a swarm. When it is emitted simultaneously with luminescent light, the robot react more intensively on filament light. This effect can be utilized in many purposes, like finding the food source, navigation or even a quick message about some global event. This communication way does not require any additional sensors, however should used only as an exception, because it essentially distorts a regular communication.

III. HARDWARE IMPLEMENTATION

In experiments we firstly looked at IR devices datasheets of many manufacturer, like Vishay, Sharp, Osram, Siemens and others. The problem is that such an important parameter as the reflection/communication distance for separate optical diodes and transistor was not specified there. The suggested spectrally matched pairs diode/transistor usually do not satisfy the requirements on opening angle. Moreover, many desired IR devices are not available on micro-component market (or require large order). Finally, we decided to purchase all suitable and available IR devices (they are not expensive, usual price is of cents) and to perform experiments with them. In the purchasing we select different groups of sensors so that results of experiments can be applied not only to the chosen sensor, but also to the whole group of sensors. In experiments we investigated the following parameters:

- Influence of ambient light on communication/reflextion;
- Reflection distance/reflection angle;
- Communication distance/communication angle;
- Communication speed;
- Size and energy consumption.

The current I_F of IR emitters was limited to 20 mA, that corresponds to I/O ports of the microcontroller. Experiments have been done by measuring a voltage V_o on the emitter of phototransistor. The emitter resistance are chosen so that at a maximal reflection the max. voltage equals $V_o \approx 5V$. Measurements have been done with the digital voltmeter ”Voltcraft M-3850”. We purchased also only such devices that provide analog output signal, therefore such popular sensors as IS471F or Sharp’s GP2Dxxx with binary output are not considered. In Fig. 6 we show some tested sensors (from over 30 pairs).

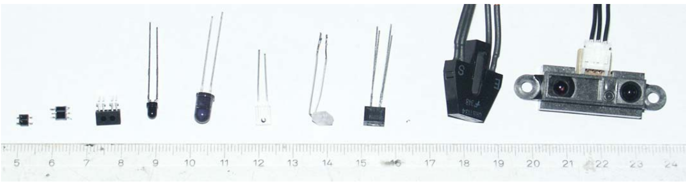
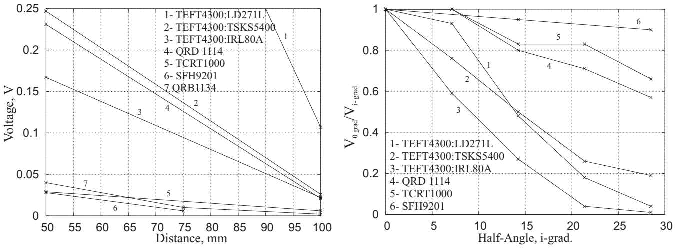


Fig. 3. *Some sensors used in experiments.*

A. Communication

The IR based signal transmission is actually not problematic, because a direct receiver-emitter optical connection provides enough IR radiation for stable communication channel. The points, that we have to be care about, are 60^o opening angle with good sector coverage and communication distance.

In experiments we used the following pairs TEST2600:TSSS2600, TEFT4300: (IRL80A, TSKS5400-FSZ, LD271L), integrated sensors SFH9201, TCNT1000, TCRT1000, QRB1134, QRD1113. Generally we tested also IR emitters with small opening angles like SFH409, but they do not satisfy the requirements. We also have several problems to isolate TEST2600:TSSS2600 optically one from another. This pair has wide vertical opening angle 120^o, so that to remove completely a leak of IR radiation in sensor was not really possible. In Fig. 4(a) we demonstrate the emitter voltage of IR receiver in dependence of distances in the ”near” and ”close” zones for some tested pairs. In Fig. 4(b) we plot a degradation of IR radiation V_{0grad}/V_{i-grad}, depending on a deviation from the cental line (V_{0grad} was measured on the central line and V_{i-grad} voltage with corresponding angular displacement, the referent distance 100mm).



(a) (b)

Fig. 4. **(a)** *Dependence between output emitter voltage V_o of IR reflective pairs and distance to the object on the central line;* **(b)** *Degradation of V_o at shifting an object from the central line in the distance of 100 mm.*

Analyzing the results of experiments, we came to the conclusion that the integrated sensors are not really suitable for this application, although they have good coverage in 60^o sector. The measured distances is only of 40-50 mm (on the brink of recognizability), and communication radius R_c is about 60-70 mm (also on the brink of recognizability). The IR emitters with opening angle of 40 and less degree do not provide a good coverage in 60^o sector. From the tested IR emitters only one TSKS5400-FSZ demonstrated acceptable coverage that can be approximated in the algorithmic way. The sensor QRD1113 shows really good results, however it was extremely sensitive even to the luminescent light, so that its further calibration represents essential difficulties. **Receiver and emitter should be optically isolated so that to provide only 60^o opening angle** (they can perceive and send till 80-90^o).

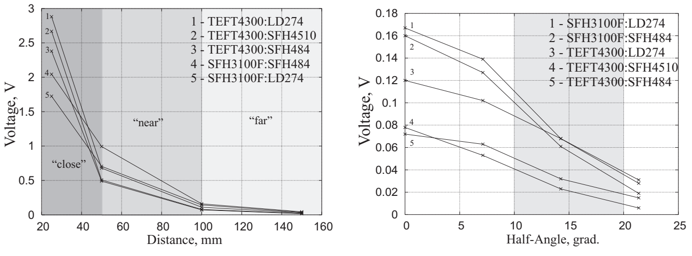
Tests of communication was performed by sending small packages with PCM modulation. The duration of ”T”-pulses was chosen to 1-0,5 ms, so that at least the rate 1000 bit/sec can be provided. The communication signal from 150 mm distance on the direct line was of 0.7-0.8 V, in different directions within 60^o not less than 0.1 V. The signal outside of 60^o was less than 0.1 V for sensors with optical isolation. In this way robots can receive very exact information about a spatial origin of signal. Communication distance can be easy reduced (or even increased) in the algorithmic way by putting some threshold on the ADC values of sensors.

B. Sensing

For sensing we choice IR emitters only with small opening angles, as e.g. TSAL6100, TSTS7100, LD274, SFH484 and SFH4510. Moreover, we also tested distance sensors, that combines emitter and receiver, such as GP2D120, QRB1134 and QRB1113. For experiments we use a plastic cube with the edge 25 mm. Sides of this cube are painted in different colors so that we can compare reflectivity depending on object's color.

The distance sensor GP2D120. As stated in its datasheet, this sensor can measure distances between 40 and 300 mm, $R_{max} = 300mm$ (within this range it delivers the values, that are independent from a color of the object, slope, and the light). The sensor is really insensitive to ambient light, however for open distances (over 300-500 mm), it produces some "background" voltage, that depends on illumination. This sensor, perhaps because of non-symmetrical construction, has completely different values on left and right part regarding the central line (symmetry of the robot).

Separated IR emitters and receivers with ambient light filter. We are going to use the same receiver for distance measurement and communication, therefore we prefer sensors wide opening angle, e.g. TEFT4300, TEST2600 ($\alpha = 60$), in the "control group" we have SFH3100F with $\alpha = 30$. Some distance measurements are shown in Fig. 5(a).



(a) (b)

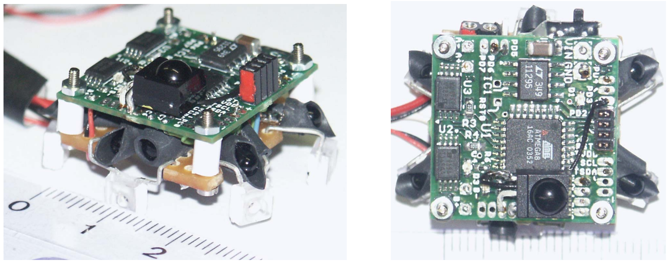
Fig. 5. **(a)** *Dependence between output emitter voltage V_o of IR reflective pairs and distance to the object on the central line;* **(b)** *Degradation of V_o at shifting an object from the central line in the distance of 100 mm.*

In the Fig. 5(b) we plot for some tested pairs the degradation of V_o in dependance on a deviation from the central line in the distance 100 mm. We see that in fact all values disappear only at the angle 30-35 grad. For 30^o radiation ray, the geometrical resolution G_{res} from Fig. 2(d) is 25-30 mm for the distance of 100 mm. The slope of degradation corves is too small to provide "abrupt boundary" of the radiation ray, needed for a good object resolution. Ambiguity in 5-10^o leads to the minimal resolution of 15-20 mm in 100 mm distance. The geometrical resolution depends also on the accuracy of robot's rotation.

The minimal recognizable distance is about 5 - 10 mm and depends on a construction of the sensor and optical isolation. Generally, a detection of the touch (contact with an object) is not possible with reflective IR sensor. In a small distance the voltage V_o in fact does not depend on the slope of objects, however highly sensitive to the color. For the black color, the V_o was reduced in 5-10 times in comparison to the white color. Therefore, for calibration of the distance sensor, all objects have to be of white or, at least, light (grey) color.

Proximity sensors underlie less requirements than the distance sensor. Primarily, they have to provide the wide 60^o opening angle with an uniform distribution of IR radiation in this sector. Desired coverage zones are "close", "near" and, if possible, "far". The delivered values have to enable a detection of obstacles in these zones. The sensors, chosen for communication, satisfy these requirement.

For color sensing we tested TSLB257, TSLG257, TSLR257 color-light-to-voltage convertors. The main problem we encountered is that the color perception as well as a communication by color LEDs cannot be done in a presence of any ambient light. The sensor cannot differentiate whether the light comes from color emitter (or reflected light from colored object) or it is an ambient light. This problem is remained unsolved. The sensors used for communication and sensing are prototyped on the sensors board, shown in Fig. 6. Experimenting with this optical prototype, we encounter several problems with optical isolation. Tubes on the receivers and montage of both boards restrict opening angle too much so that communication-dead zones appear in the corner areas. This prototype is currently under redesigning.



(a) (b)

Fig. 6. **(a)** *The megabitty board and the sensors board used in the prototype of a microrobot;* **(b)** *6-directional sensor system for directional communication and proximity sensing.*

IV. SOFTWARE ASPECTS OF COMMUNICATION AND PERCEPTION

After describing the IR hardware solution, we focus on the "software support" of communication and perception.
Communication. As already mentioned, a propagation of information through a swarm represents the main problem (see for details [8]). We suggest to solve this by using directional communication with specific logical protocol. In Table III we collect some points of logical communication in swarm.

On the level of physical transmission the problem of communication is related to a choice of modulation/transmittion approach suitable for the IR based signal transmission. In experiments we choose pulse code modulation (PCM) approach for remote control and inter-robot communication with half-duplex data exchange. In remote control scheme, the input of PCM sensor (TSOP4836, 36kH subfrequency) is connected with the external interruption input of the microcontroller. Activating the interruption on the failing or rising edges we can differentiate between T and information impulses. Timer counts during information impulses so that we can easily recognize logical "0" and "1". Inter-robot communication utilizes similar principle, however does not modulate the signal with subfrequency.

Level of logical communication	**Known solution**	**Problems in swarm application**
IR based signal transmission	Simple impulses PCM, PWM IrDA	Small channel capacity Problems with encoding Specific hardware
Comm. protocols, propagation of information	Package-based Pheromone-based	Problem of routing Small infom. capacity
Subsystems that require communication	Collective perception Coordination Decision making	—
Creating and supporting SPPN	Small-area swarms Inter-clusters exchange Active SPPN	Not realistic Req. too much energy Robots overhead

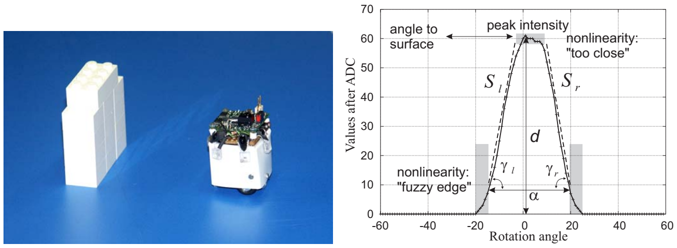
TABLE III

Levels of logical communication in swarm.

Level of logical communication protocols concern the propagation of information in swarm. We investigated several approaches like package- and pheromone-based communication, some indirect communication mechanisms. The main problem of package-based logical communication is a routing of messages through a swarm and providing a context of messages. In [8] we suggest to use a context diffusion approach, that is similar to ”spreading a virtual pheromone”. As demonstrated by experiments, in this way we can solve at least a part of problems related to global propagation of information. Propagation of information can essentially be improved when at least a part of robots is contained within the communication radius of each other (so-called the swarm peer-to-peer network (SPPN)). More generally, creating and supporting SPPN, the robots are able for quick communication, global navigation, spatial over-swarm perception and so on. Therefore this point is open for further research.

Perception. The principle of perception is the following [5]. As soon as a robot detects (by means of proximity sensors) an obstacle in front of itself, it stops and rotates on the angle of 60 degree left. After that it switches on the high power IR emitter and scans the obstacle by rotating 120 ^{o} right. During this scanning it writes the values of distances each 1 degree into an integer array. In this way 120 values describe a visible geometry of the encountered obstacle. In Fig. 7 we demonstrate some geometries of obstacles and the scanned values of distances.

For surfaces recognition we can use the following features.
1. *The angel* α, which represents the scanning angle between the first visible edge and the last visible edge of the surface;
2. *The peak intensity of the diagram* I_{max}. This corresponds to the maximal intensity of reflecting light and, in turn, to the minimal distance d between the surface and the microrobot. For the most types of surfaces (beside convex corners) this minimal distance is measured as a perpendicular to a surface. This feature allows calculating the visible size of a surface by using trigonometric relation;
3. *The left and right slopes*, denoted as γ_l and γ_r. We concluded that the slope is also useful for identifying the type of the surface (unlimited, big, small). They are calculated as slopes of the approximation lines S_l, S_r. The slope denotes also the ”degree of a distance decreasing” and enable us to identify so-called ”convex surfaces” that cannot be recognized in the trigonometrical way;
4. *The position of the ”centrum” of the IR diagram* P_{imax} in relation to the rotation angel (”0” point). Displacement of the centrum points to a slope between the from of robot and surface. In this way we can identify a global orientation of the microrobot.



(a) (b)

Fig. 7. *Prototype of the microrobot ”Jasmine” scans different surfaces, d is a distance to surfaces* **(a)** *Scanning of the finite-size surface, object 48 mm;* **(b)** *IR diagram for this surface and different features that can be used for identifying surfaces.*

As mentioned in Sec. II, the IR based perception system is extremely nonlinear. Now we formalize these nonlinearities and their impact on the mentioned features.
1. *Nonlinear thickness* of the IR radiation ray and so different distribution between high-energy beam and low-energy beam. The first effect of this nonlinearity consist in spreaded edges (Fig. 7(b)). This nonlinear effect can be absorbed by calibration. The second effect is that at scanning many-surfaces geometry (e.g. a gap between objects) a robot cannot reliable differentiate between 2-concave surfaces and surfaces that belong to different objects;
2. *Nonlinear measurement for small distances*. As known from other IR distance measurement systems (e.g. [3]), the maximal intensity of measurement lies in 10-25% before the front of IR receiver, after that the intensity goes down (therefore small distances cannot be measured by these systems at all). Due to the specific constriction and the application of high-power GaAs/GaAlAs emitter, this effect is removed. However the surfaces that lie less than 40mm away from a robot are represented only by values 245-250, for ”close” measurement (30mm) we get a flat horizontal diagram;
3. *Nonlinear accuracy* of distance measurement. This requires nonlinear correction (it is done as a look-up table) of trigonometric relation in dependence of distance. However this nonlinearity is very ”tricky”. Even when a robot starts a measurement in the ”good” area of 40-120mm, a part of geometry can lie over 150 or 200 mm away. The effect of this nonlinearity appears in unreliable identification of many-surfaces geometry;
4. *Nonlinear rotation* of the robot. This can lead to different left γ_l and right γ_r slopes even for symmetric surfaces. The

most easiest solution here is to calibrate γ_l and γ_r;

5. *Nonlinearity in measuring convex surfaces*. The identification of all types of convex geometries is performed by γ_l and γ_r. The difference between slopes for e.g. round objects, convex corners and finite-size flat objects is small, moreover due to a nonlinear intensity diagram, these slopes changes with distances ! This problem has some basic character and we hardly belief that with all nonlinearities of IR perception we are able to reliable identify the type of convex surfaces.

The developed algorithms, based on the discussed features and nonlinearities, allow classifying surfaces. For all types of geometry, the robot estimates also a probability of correct recognition for further multi-hypotheses classification and collective perception. In [5] we describe the collective perception based on the Dampster-Shafer evidential reasoning.

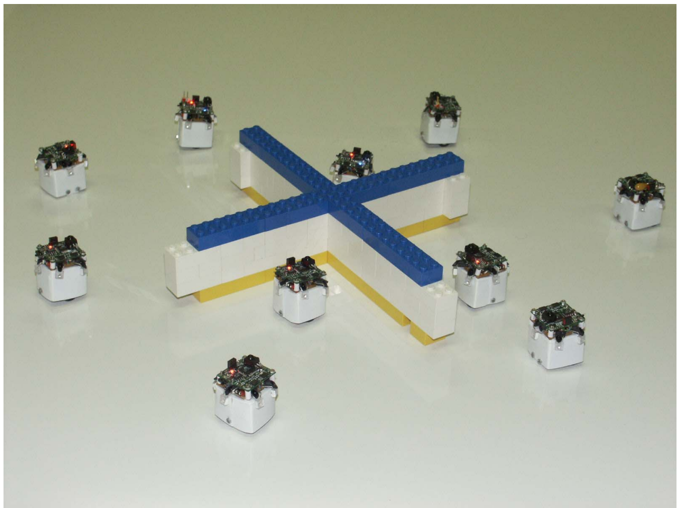


Fig. 8. *10 prototypes of the microrobot "Jasmine" in preliminary experiments.*

Preliminary experiments. For performing preliminary experiments we prototyped 10 microrobots (with 2 DC motors and 2x3.7 V 250 mA/h Li-Po accumulators which allow 2-2.5 hours of autonomous work), see Fig.8. The experiments deal primarily with collective perception and global information propagation. The experiments demonstrate that the developed solution is suitable as the flexible and low-cost test platform for exploring real swarm behavior. Analyzing the experimental results, we are now improving the prototype and preparing it for "serial" production.

V. CONCLUSION

In this work we demonstrated the development of IR based system for communication and perception for the microrobotic test platform $23 \times 23 \times 28$mm. We encountered that small integrated transistor-diode pairs (appropriate for micro-applications) are not suitable as distance, proximity and communicating sensors. In the tested phototransistors with 60^o angle, we choose TEFT4300 (60^o, collector light current 3,2 mA, 875...1000 nm), TSKS5400-FSZ as IR emitter for proximity measurement and communication (60^o, 950 nm, 2-7 mW/sr) and GaAs/GaAlAs IR emitter TSAL6100 (20^o, 950 nm, >80 mW/sr) for distance measurement. Proximity sensors are very small (emitter 5x5x2.65 mm and receiver 4,5xϕ3 mm).

The developed software for IR system allows directional communication (R_c=0...140, 300mm(max)) with many principally different communication protocols (e.g. package- and pheromone-based), diffusion of information in a swarm. The perception is able for 6-x directional sensing of obstacles within 100mm, classification of surfaces geometry within 150-200mm and represents a basis of collective perception. We implemented several approaches for a global propagation of message's content/context ("context-aware communication") and for collective classification as well as tested them in a small group of microrobots (more details on hardware and software can be found on project and authors' homepages).

As demonstrated by experiments, these "minimal capabilities" of a robot allow the whole robotic group to perform many collective activities (collective navigation and coordination, cooperative acting and perception and so on). The developed platform is extremely cheap (the complete cost is under 100 Euro) and available in micro-component market. Using pre-soldered parts, like megabitty and sensors boards, assembling is easy even for inexperienced personal. In this way this solution represents a good microrobotic platform with extended swarm capabilities for exploring a phenomenon of swarm intelligence in real experiments.

REFERENCES

[1] V. Balzani, M. Vetturi, and A. Credi. *Molecular Devices and Machines. A Journey into Nanoworld*. Wiley-VCH, Weinhaim, Germany, 2003.

[2] E. Bonabeau, M. Dorigo, and G. Theraulaz. *Swarm intelligence: from natural to artificial systems*. Oxford University Press, New York, 1999.

[3] G. Caprari and R. Siegwart. Design and control of the mobile micro robot alice. In *Proc. of the 2nd Int. Symposium on Autonomous Minirobots for Research and Edutainment, AMiRE'2003*, pages 23–32, 2003.

[4] I-Swarm. *I-Swarm: Intelligent Small World Autonomous Robots for Micro-manipulation, 6th Framework Programme Project No FP6-2002-IST-1*. European Communities, 2003-2007.

[5] S. Kornienko, O. Kornienko, C. Constantinescu, M. Pradier, and P. Levi. Cognitive micro-agents: individual and collective perception in microrobotic swarm. In *Proc. of the IJCAI-05 Workshop on Agents in real-time and dynamic environments, Edinburgh, UK*, 2005.

[6] S. Kornienko, O. Kornienko, and P. Levi. About nature of emergent behavior in micro-systems. In *Proc. of the Int. Conference on Informatics in Control, Automation and Robotics (ICINCO 2004), Setubal, Portugal*, 2004.

[7] S. Kornienko, O. Kornienko, and P. Levi. Generation of desired emergent behavior in swarm of micro-robots. In *Proc. of the 16th European Conf. on AI (ECAI 2004), Valencia, Spain*, 2004.

[8] S. Kornienko, O. Kornienko, and P. Levi. Collective ai: context awareness via communication. In *Proc. of the IJCAI 2005, Edinburgh, UK*, 2005.

[9] C.R. Kube. A minimal infrared obstacle detection scheme. *The Journal for Robot Builders*, 2(2):15–20, 1996.

[10] M.J. Mataric. *Interaction and Intelligent Behavior, PhD thesis*. Massachusetts Institute of Technology, 1994.

[11] Megabitty. see http://groups.yahoo.com/group/megabitty/. 2005.

[12] S. Suzuki, H. Asama, A. Uegaki, S. Kotosaka, T. Fujita, A. Matsumoto, H. Kaetsu, and I. Endo. An infra-red sensory system with local communication for cooperative multiple mobile robots. In *Proc. of International Conference on Intelligent Robots*, pages 220–225, 1995.