Optical Networking in a Swarm of Microrobots

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Abstract. Swarm Microrobotics aims to apply Swarm Intelligence algorithms and strategies to a large number of fabricated miniaturized autonomous or semi-autonomous agents, allowing collective, decentralized and self-organizing behaviors of the robots. The ability to establish basic information networking is fundamental in such swarm systems, where inter-robot communication is the base of emergent behaviors. Optical communication represents so far probably the only feasible and suitable solution for the constraints and requirements imposed by the development of a microrobotic swarm. This paper introduces a miniaturized optical communication module for millimeter-sized autonomous robots and presents a computer-simulated demonstration of its basic working principle to exploit bio-inspired swarm strategies.

Keywords: micro-optics, optical communication, microrobotics, swarm intelligence.

1 Introduction

Microrobotics is a field of the scientific and technological research that aims for the development of miniaturized autonomous or semi-autonomous systems. Microrobotics has a particular relevance in the development of a relatively new scientific discipline named *Swarm Robotics*. This aims to apply *Swarm Intelligence* strategies [1] to a large number of robotic agents, allowing collective, decentralized and self-organizing behaviours of the robots, possibly leading to a global, often bio-inspired, intelligent behavior of the swarm on the base of few simple basic rules, while considering issues of robustness and scalability. It is indeed in the perspective of miniaturization that Swarm Robotics becomes meaningful, leading to the concept of *Swarm Microrobotics*. Actually, microrobots have by construction very limited capabilities, thus they need to operate in very large groups, or swarms, in order to have any appreciable effect on the "macroworld". In order to produce a large number of them, mass-fabrication and mass-assembly by means of Microtechnologies should be pursued.

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The cooperation between swarming agents is the key to the accomplishment of a desired task of the swarm. Communication plays a primary role in that, requiring important features to the communication system, without demanding too high resources. Communication capabilities in a microrobot are strongly limited by the microrobot size and power available on board. The first implies that only miniaturized communication systems can be integrated, while the latter imposes strict limits on communication distance and bit-rate. In addition, in order to exploit mass-fabrication, the system itself has to be relatively simple to allow automatic fabrication and assembly procedures. Following these constraints and a vast survey of possible communication technologies, optical communication demonstrated to be currently the only suitable and feasible solution for millimeter-sized microrobots. Indeed, also some of the most relevant multi-agent or swarm systems of inch-sized microrobots exploit (mainly) optics as a communication mean, e.g. iRobot [2], Alice [3] and Jasmine [4] robotic swarms.

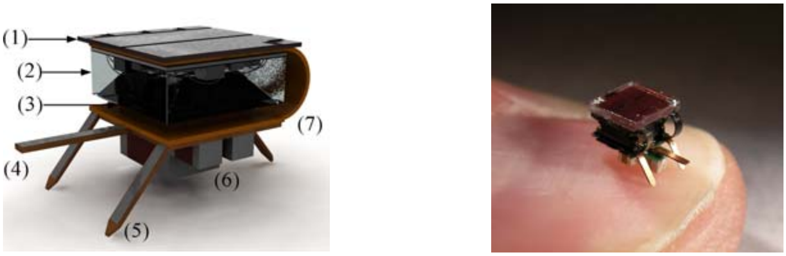
Up to author's knowledge nobody has never attempted the mass-production of optical communication modules for millimeter-sized autonomous microrobots as those developed in the I-SWARM project.

1.1 The I-SWARM Project

The challenge to develop a miniaturized communication module to be integrated in (one of) the up-to-date world's smallest autonomous robot has been attempted in the frame of the I-SWARM project [5] [6], under the European Future and Emerging Technologies (IST-FET) Programme. The project aims to mass-produce autonomous millimeter-sized microrobots, which can then be employed as a "real" swarm capable to demonstrate observable emergent self-organization effects similar to those observed within ecological systems like ant states, bees colonies and other insect aggregations.

Only a few millimeter-sized autonomous robots (with limited functionalities) have been demonstrated in literature, e.g. [7], however, none of them approached the problem from a mass-production viewpoint. Actually, the concept of Swarm Microrobotics becomes (particularly) meaningful and powerful in correlation with this last issue.

The I-SWARM microrobots consist of a stack of assembled chip-modules for a whole size of about $3 \times 3 \times 3\ mm^3$. An overview of the robotic modules and assembly process is in [8]. One of the final CAD design of the microrobot and a first prototype are reported in Fig. 1. Several tens of microrobots have already been assembled with an automatic machine-based process and are currently under testing. Each robot has a weight and volume of less than 70 mg and 23 mm^3 respectively. Although complete functionality of assembled robots is still heavily affected by the yield of the fabrication of each modules and of the assembly process itself, it is due to point out one of the most relevant results of the project from the hardware viewpoint: the establishment of a (preliminary) method for mass production and assembly of "chip-robots", a goal envisioned by some robotic experts in the past, e.g. [9], but a challenge never completely faced.



(a) (b)

Fig. 1. CAD models of a final version of the I-SWARM autonomous microrobot; a) CAD drawing of the fully assembled robot (© P. Corradi (2007)): (1) Solar cell for energy scavenging from a double-lamp system equipping a custom small arena where microrobots will operate; (2) Optical communication module [10] [11]; (3) Electronics (Application Specific Integrated Circuit - ASIC) [12]; (4) Vibrating contact sensor: a vibrating cantilever with feedback sensor to be employed as touch-sensor to locate object/obstacles [13]; (5) Piezoelectric P(VDF-TrFE) legs, which are made vibrating for moving the robot [14]; (6) Capacitors; (7) Flexible printed circuit (FPC) backbone; b) One of the produced I-SWARM microrobots on a human thumb nail; this robot version is slightly different from the CAD model in (a) (courtesy of the I-SWARM Consortium and Uppsala University)

2 A Miniaturized Communication Module for Microrobots

Bio-inspiration has been the original approach in the effort to conceive a communication system that could let the development of swarm strategies demonstrated by some insects (e.g. ants, bees, wasps and termites). Therefore, initial work was focused on studying and trying to technologically conceive devices able to reproduce the interaction systems and methods that nature has evolved among insects of a same swarm. One of the most diffused communication systems used in natural swarms is based on the release of a chemical called *pheromone*. This demonstrated to be an extremely efficient technique in nature to develop emergent behaviours in swarms. However, the technical development of systems able to reliably release and detect chemicals along the time is a critical issue. As a consequence, several attempts to design communication systems for millimeter-sized robots were based on standard technological approach such as radio wave transmission or magnetic induction (e.g. [15]), however, only optics showed to be feasible according to the space and power constraints on board the microrobot (where the communication module has to share with the locomotion module a power budget of less than 0.8 mW at 3.6 V, and integrated capacitors can guarantee only very short and limited high power pulses for information transmission) and suitable for developing swarm strategies, mainly due to its feature of directionality in signal transmission.

In literature, there are some relevant examples of miniaturized communication systems (more conceived as nodes in communication networks rather than for equipping microrobots). In the frame of the *Smart Dust* project a device has been demonstrated based on a system of passive reflection of a LASER-based optical signal [16]. The system disadvantageously requires high voltages (about 100 V) for actuation. A similar miniaturized communication system has been introduced by the *Speckled Computing* project [17], but to the authors' knowledge not a single prototype has been built so far. Moreover, both the mentioned systems cannot assure proper information broadcasting in all the directions as required by swarm applications, because they are conceived more for far-range and focused optical emission. In addition, the conceived architecture is not likely to be easily produced by means of mass-fabrication processes, a basic requirement for the development of a swarm of microrobots.

2.1 Hardware Description

The optical module was completely designed taking into account mass-fabrication issues, and aiming at minimize the architecture, while reaching a sufficient functionality. The final design consisted of a 9 mm^3-body composed of a thin substrate, sub-mm sized photoemitter and photodetector dies (ELC-870 series and EPC-880-0.5 respectively, from Epigap, working in the $870-880\,nm$ light range), which are integrated and wire-bonded along the borders of the substrate and controlled by the microrobot ASIC, 0201-sized surface-mounted resistors in the centre and a reflecting structure placed over the substrate, aimed at deflecting the incoming signals towards the photodetectors and at deflecting the signals generated and vertically emitted by the photoemitters toward the surroundings. The mirror structure was fabricated as a moulded transparent polymer body with a central pit with reflective 45°-sloped walls, covering and embedding the assembled devices. A CAD design is shown in Fig. 2(a). In Fig. 2(c) some of the final and fully functional fabricated optical modules: the polymer mirror looks black-colored because a visible light-blocking black-dye (Epolight^{TM} 7276A) was mixed into the polymer for ambient light rejection (up to about 850 nm). The pyramidal pit of the mirror were sputtered with chromium, in order to form reflective surfaces to deflect the light.

(a) (b) (c)

Fig. 2. a) Final CAD design of the optical module (size: $3 \times 3 \times 1.2\ mm^3$), with LEDs (small boxes) and photodiodes (larger boxes) along the borders of the substrate, and resistors in the center; the modules has to be turned up-side down in the microrobot, see Fig. 1(a); (b) Mass-produced optical modules diced by LASER machine (mirrors are not sputtered); (c) Close view of mass-produced optical modules (one is turned up-side down showing the bottom-side electrical contacts) with metal sputtered mirrors.

2.2 Communication Properties

The optical properties of the communication module were firstly simulated before fabrication and experimentally characterized afterwards [11]. Tests were carried out to determine its radiation pattern and also its communication range, both in laboratory conditions and under the nominal illumination conditions of the I-SWARM arena. In Fig. 3 the set of measured points around the module with the same detected value of emitted light intensity, starting from a fixed value (e.g., the free-error communication intensity value at 15 mm distance) is reported and compared to the corresponding theoretical pattern reported as dotted line (and calculated starting from the consideration that the emission from each side of the optical module is Lambertian). The measured pattern results wider on the LED side due probably to bulk and surface scattering of the light in the polymer of the optical module. A significant overlapping of the free-error communication zone between adjacent sides of the module would evidently occur. This feature might be advantageous in order to improve the angular resolution in communication, by exploiting serial emission of the four LEDs (each identified with a specific code, see the next section 2.3) of the transmitting microrobot: in the signal-overlapping zone the receiving microrobot will be able to receive, consecutively in time, both the signals emitted by adjacent sides of the microrobot, thus better understanding the relative orientation of the transmitting microrobot.

For signaling, a defined digital protocol has been used [18], where only extremely short pulses (30 μs long) are emitted. Each single bit is started by a pulse; if this pulse is followed by a second pulse (after a software-adjustable time period), then the symbol is interpreted as a logic '1', if the second pulse is missing,

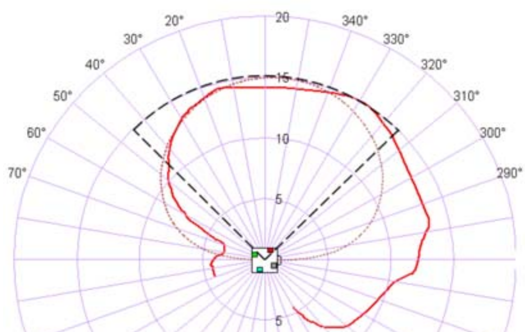


Fig. 3. Polar plots of the error-free communication pattern generated by one side only of the optical module: the continuous line plots measured data starting from a maximum distance of 15 *mm*; the dotted elliptical-like line represents the calculated radiation pattern; the sectioned darker line, defining a 90°-wide circular sector, is the radiation pattern as theoretically considered in the algorithms presented in the following and as it is modeled in the simulation described in the section 3. The module size in the centre is exaggerated for clarity (it should be only a central point). Units are degrees for the angles and *mm* for the distance.

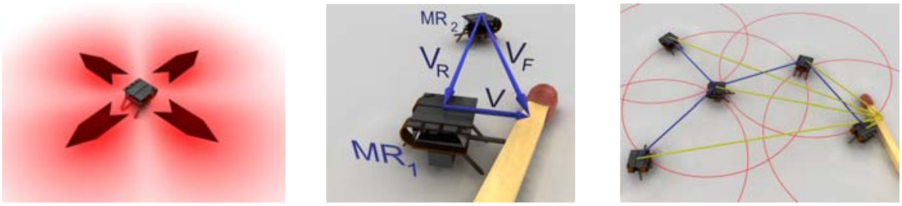
as a logic '0'. A beginning of a data frame is marked by three consecutive pulses. The ASIC hardware supports a frame length between 1 and 32 bits. Bit rate can be adjusted by software from 83 *bps* to 2083 *bps*. The average maximum power consumption on a 32-bit frame at the lowest transmission speed is $36.6 \mu W$ ($438.5 \mu W$ at 1 *Kbps*), with a peak power consumption of 7.2 *mW* (2 *mA* at 3.6 *V*). Error-free directional communication capability was demonstrated with the optical modules up to 20 *mm* in standard laboratory conditions with a supplied current of 2 *mA* and using standard laboratory electronics. By using the ASIC both for transmission and reception the same distance decreased down to 9 *mm*. Due to powering illumination in the final arena set-up, the inter-robot communication distance was further reduced to 4.5 *mm*. Several realistic improvements to increase performances of the whole system have been considered for future works.

2.3 A Basic Communication Strategy between Microrobots

The introduced optical system allows a basic directional communication strategy for both collision avoidance between microrobots and a cooperative behavior without any external supervision, as described in the following. A similar technique is described in [19] for multi-agent robotic applications, but for much larger robots. During communication each LED belonging to one microrobot is identified with a particular bit string; in the case of four LEDs, two-bit strings are enough: 00, 01, 10, 11 (Fig. 4(a)). In this way surrounding microrobots can detect not only the presence and position of one or more microrobots, but also understand if it/they are on a direct collision course and react accordingly. The mentioned cooperative strategy is illustrated in Fig. 4. The strategy is based on the following steps: a microrobot MR_1 finds a target or obstacle and a microrobot MR_2 enters MR_1's communication range. In a more general configuration, the microrobot MR_{N+1} needs to know:

A. The relative direction of the microrobot MR_N (which is understood depending on which of the MR_{N+1}'s photodiode(s) receives the signal);
B. The relative orientation of MR_N (received by bit communication);
C. The target direction vector with reference to MR_N (received by bit communication).

Combination of points B and C transposes the vector of the target from the reference of MR_N to the reference of MR_{N+1}. In this way the vector named $\boldsymbol{V}$ in Fig. 4(b) is acquired from MR_{N+1} relatively to its own reference system. The final vector $\boldsymbol{V_F}$ for the target direction is obtained by calculating the vector sum of the components of the acquired vector $\boldsymbol{V}$ and the vector $\boldsymbol{V_R}$, introduced in point A. This allows each microrobot to know the direction to the target (and eventually also the distance, if $\boldsymbol{V_R}$ is thought to have a known value, proportional to, for instance, the detected intensity of the received signal). Fig. 4(c) shows an example of the propagation of this strategy to several members of the swarm and the formation of a vector trail. In this basic form, it is possible to think that as soon as the microrobot MR_{N+1} enters the MR_N's communication range, it stops



(a) (b) (c)

Fig. 4. (a) Representation of a theoretical emission pattern of the optical module mounted into the microrobot; (b) Vector sum for reconstruction of the direction of the target (e.g. a match): $\boldsymbol{V_F} = \boldsymbol{V_R} + \boldsymbol{V}$; (c) Optical network established inside the swarm: darker vectors are the $\boldsymbol{V_R}$ for each microrobot and define the forming trail; the circles defines the theoretical border of the communication range for each microrobot. © P. Corradi (2007)

and starts to forward the signal. In this way the technique allows information broadcasting within the swarm, creating a motionless communication network, that extends in time, thus increasing progressively the probability that other microrobots could meet it and, therefore, receive information.

The main issue regarding the working principle of the developed communication module and the introduced basic communication strategy consists in a poor angular resolution for the identification of direction and relative orientation between microrobots, because only four directions basically can be discriminated. Nevertheless, the bio-inspired swarm algorithm, presented in the next section 3, which is based on these basic rules, demonstrates in simulations collective swarm behaviours and the establishment of an emergent network, which, in this case, is also "mobile" (microrobots keep moving while receiving messages). Although the optical properties of the described communication module are modeled in the simulation in a simplified way (in particular, as clearly visible in Fig. 3, the modeled radiation pattern does not reproduce a considerable part of the measured optical pattern), the results are significant because they introduce a preliminary demonstration of the possibility to implement swarm strategies on the base of the minimal communication module developed and the simple rules described. The same strategies will be tested in the final physical microrobotic swarm as soon as enough fully functional microrobots will be available.

3 A Bio-Inspired Vector-Based Swarm Algorithm

For swarm-robotic algorithms, nature offers a variety of sources of inspiration by providing a multitude of biological solutions to "swarm problems". It is desired to find algorithms that are easy enough to be implemented with the limited computational capabilities available on board autonomous swarm microrobots. Besides that, the algorithms should be robust enough to work in a noisy environment, sensed through imperfect sensors, flexible enough to be able to deal with rapidly changing environments. Obviously, the algorithms should also scale well to be used in ever-increasing swarm sizes, as they are used in today's swarm robotics [20]. These constraints require a decentralized local-neighbour based communication, as it is frequently found in natural swarm systems [21]. On the base of the features of the introduced communication module and on the described vector-transmission technique, we describe here the basic principles of a bio-inspired communication and navigation algorithm, which is based on simple vector communication, as it is found in honeybees [22], and on vector summation, as it is found in the desert ant Cataglyphis [23] [24]. We demonstrate here, how this vector-based algorithm can allow hundreds of robots to allocate themselves at the right places in the arena and to organize themselves into self-organized trails in a multi-source/one-target scenario.

The algorithm is based on the communication of simple vectors within a swarm of microrobots equipped with the described communication module. This was modeled in the simulations merely at a functional level, characterized by a set of 4 light emitters and sensors, which emit and perceive horizontally in four directions (front, rear, left, right) with 90° between the central transects of each emitted light beam. No light physics was implemented at this stage, the simulation limited to show the emergent cooperative effect based on the theoretical working principle of the optical module, although several realistic conditions were implemented, see in the following. The communicated messages consist of 3 integer values and 3 boolean signals: The Boolean (On/Off) signals indicate the internal status of the sending robot, two integer values are used for communicating the vector towards the target, and one integer value is used as a hop-count, which allows to identify the "age" of the message. The necessary calculations performed within the robots are simple additions of vectors as well as "if-else" statements.

The testbed for the proposed algorithm is the simulator "LaRoSim v.66" [25], which is a multi-agent bottom-up simulation of a swarm of I-SWARM robots. The robotic swarm is tested in a cleaning scenario, in which the robots have to encounter dirt areas (sources), attract other robots to these source areas and then move on an as-short-as-possible path to a designated dump area (target). The robots can sense the source area and the target area only if they are already located there and can then communicate messages to other nearby robots within a circular neighbourhood of 3.5 robot-diameters. The vector-based algorithm is described as follows:

1. All robots start unloaded (no dirt particles loaded) at randomized positions in the arena, are headed in randomized directions, and move straight ahead.
2. If a robot senses another robot or an obstacle in front, it turns away of the encountered obstacle.
3. If an unloaded robot realizes that it is located on a source area, it picks up a particle and emits a specific boolean signal (*signal-1*) and an additional signal coding for the LED used. An additional hop-count is also attached to each message. As this robot is located directly on the source area, the hop-count is set to 1, what indicates information of the highest possible quality. After some time-steps, this robot picks up a dirt particle and significantly

changes its internal status this way. See step 7 for this robot's further behavioural rules.

4. If another robot receives the *signal-1* and the corresponding orientation code, it calculates the relative angle to the robot that is located on the source area and adds the vector ($\boldsymbol{V}$) that was transmitted by communication. This way, the receiving robot can calculate the resulting vector ($\boldsymbol{V_F}$), which should point directly to the robot located on the source. The robot then starts to emit another specific boolean signal (*signal-2*), which indicates that the robot is not located on the source area, but is receiving "high-quality" information directly from a robot that is located on the source area. It also emits the vector towards the source area, as well as a beam-specific (LED) code. At the end of the message, a hop count (now increased to 2) is sent.
5. Other robots can receive this message and can update their own vector towards the source area, as long as the hop-count of the received message is below or equal to the already stored information.
6. All unloaded robots that receive such a vector message turn towards the location of the source area and move a small distance forward before they receive new information, calculate new resulting vector by vector summation and they transmit this new vector again to their neighbours.
7. For describing the behaviour of loaded robots, the same rules as mentioned in the steps 3-6 apply, except that the term "unloaded" has to be replaced by the term "loaded" and the term "source" has to replaced by the term "target": These robots move in trail formation from the source areas (dirt) towards the target areas (dumps). As soon as they reach the dump area, they drop the carried dirt particle there, change their status to "unloaded" and continue with step 1.

For testing this algorithm in the simulator under realistic conditions, an error in communication (*P_break_communication*) was assumed. Furthermore we assumed that robots cannot measure distances and could not perform angular measurements to other robots, they can only discriminate the side the other robot is located relative to themselves (front, rear, left, right) by evaluating the photodetector that received the message from the other robots. For calculating the vectors to other robots, the robots use a "standard distance", which reflects the half of the maximum communication range, and they use a "standard angle", which reflects the median transect of the area covered by the receiving photodetector. To allow outdated (not-reinforced) information to leave the system, two additional rules were implemented: With a given probability of 20%, a robot spontaneously forgets its information and refreshes its internal memory by accepting information from other nearby robots. Except for this case, robots accept only communicated vectors with hop-counts less or equal to their own stored "old" information. To prevent the robots from aggregating too densely in specific parts of the arena (e.g. source areas, target areas), we prevented a fixed fraction (10%) of the robots from navigating towards the points that are communicated by the vectors. These robots ("scouts") perform just the random walk and communicate with neighbours, thus their important role is to provide a bridge in the swarm network from one aggregation area to the others.

3.1 Results

The simulated arena setup in the cleaning scenario consists of an arena wall (outer boundary), four dirt areas (sources) in the corners of the rectangular arena, and one central target area (dump), see Fig. 5.

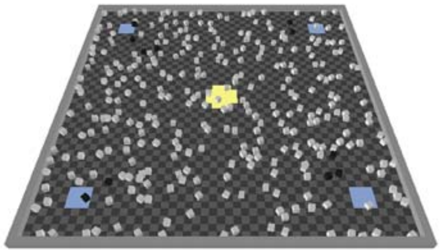


Fig. 5. Screenshot of the simulation scenario: Light-grey boxes indicate unloaded robots. Dark-black boxes indicate loaded robots. They move on a chessboard-like arena, where every grey square represents a patch. In the corners of the arena, four rectangular dirt areas (sources) are shown. In the center of the arena, a cross-shaped dump area (target) is shown. Robots should transport dirt particles from the sources to the target in as direct as possible trails.

By varying the parameter *P_break_communication* and the number of robots on the arena (i.e. the swarm density in the arena, expressed in percentage by the parameter *swarm_density*), we show the robustness of the algorithm. To visualize the results, we tracked the paths of all loaded robots and coded them as shades of grey on the arena floor. The darker an area is, the more loaded robots have been located on that patch of the arena. As Fig. 6 shows, both parameters affect significantly the directness of the robots' motion. However, under all tested circumstances the robot swarm was always able to form a trail heading clearly towards the central dump area.

As the probability of communication breaks increases (Fig. 6, from left to right column), the trails get (slightly) wider, indicating less optimal navigation towards the central target area. As the swarm intensity increases (Fig. 6, from top to bottom row), the global swarm behaviour changes: With a density of 5% ($swarm\_density = 0.05$, corresponding to a swarm size of 109 robots, Fig. 6(a),(b),(c)), no trails emerge at all. The robots' motion show just random trajectories, because the distances between robots are too large to allow longer chains of robot-to-robot communication, thus no network is estalished. With a swarm density of 15% (i.e. 328 robots, Fig. 6(d),(e),(f)), the robots clearly approach the central target. The smaller the communication failure rate, the clearer the emerging trails are (compare Fig. 6(d),(e),(f)). With a *swarm_density* of 25% (i.e. 547 robots, Fig. 6(g),(h),(i)), still prominent trails emerge. But most robots accumulate in a ring-shaped structure around the target, not on the target area itself. The high swarm density leads to the fact that a large number of robots that were initially located on the target area got trapped by the dense trail

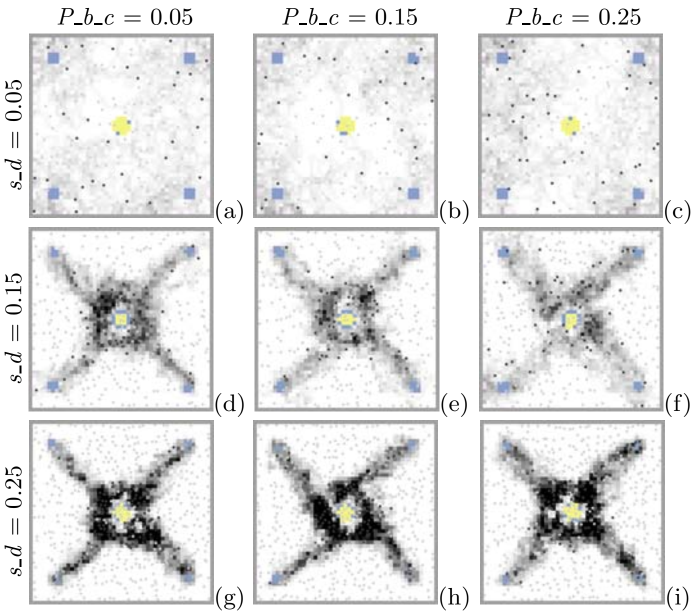


Fig. 6. The effect of the parameters *swarm_density* (*s_d*) and *P_break_communication* (*P_b_c*) on the directness of the swarm's navigation

heading towards this target area. Thus, a robot density of 15% was found to be a near-optimal swarm-density for the given scenario.

Finally we wanted to investigate how these parameters affect the efficiency of the robotic swarm. For all the 9 parameter combinations, corresponding to Fig. 6(a)-(i), the number of picked-up and delivered dirt particles was measured. The result states that a swarm density of 15% and a value of *P_break_communication* of 5% is optimal for particle delivery. A higher swarm density can increase the number of picked-up dirt particles but results in a significantly lowered number of delivered particles due to the emergence of the dense ring-shaped robot trail around the delivery area.

4 Conclusions

We have introduced a novel mass-producible miniaturized $3 \times 3 \times 1.2\ mm^3$ communication system for swarming microrobots, whose architecture allows the exploitation of a simple communication strategy based on the transmission of vectorial information. The possibility to form communication networks between more and more tiny mobile robots is indeed based on solutions of minimal, thought functional, communication hardware and the exploitation of distributed and decentralized intelligence in suitable large multi-agents systems or swarms. The presented bio-inspired vector-based algorithm is a robust and computational easy algorithm, which bases on the working principle of the developed optical module and requires only very limited computational power of the robots it is executed on. With 3 Boolean and 3 integer values (per motion cycle), the required bandwidth of communication is low (less than 17 *bps*). Simulation results show that using simple navigation rules and limited nearest-neighbour communication, a desired and well directed collective swarm behaviour, e.g., trail formation, can be achieved. The robotic swarm demonstrated to work with a variety of parametrizations, as well as with a high number of target areas, leading to a complex pattern formation of autonomously emerging trails of loaded robots all heading towards a single target, starting from several "trail sources".

Future works include modeling the measured emission/reception radiation pattern of the fabricated optical module in the simulator, and, finally, experimental tests with the fabricated microrobots.

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