An Optical Interface for Inter-Robot Communication in a Swarm of Microrobots

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Abstract— **It is described the optical communication interface for short-range communications of robots in a microrobotic swarm between thousands of units. The robots, of 27 mm^3-size, will be deployed in an arena of A4 sheet size with controlled illumination conditions. The communication between robots is done via IR light. The interface can handle variations of IR background light from point to point in the arena, deals with robot different orientation and distance, i.e., the amplitude of the signal to be detected, and with interferences of other robots. The interface has been designed to manage the low energy available in the robot.**

Index Terms— **Swarm, robot, communication, transimpedance amplifier, low power.**

I. INTRODUCTION

Miniaturized robotic systems open new challenges not only in mobile robotics but also in many related areas such as sensor systems, locomotion, energy supplying, communications and so on [1]. Current state of the art of miniaturized robots is in 3x3x3 mm^3 achieved in the I-Swarm European Project [2]. In such a project one thousand of mm^3-sized microrobotic units are being developed. The robots are completely autonomous and are designed to allow the development of swarm behaviors in the colony.

A swarm of robots consists of many small and simple robots working together to accomplish a task more efficiently than a single robot [3]. Hence, the swarm behaviour results on the apparition of swarm intelligence, as can be seen in biological communities like ants, bees, etc [4]. The collective behaviour in a swarm emerges from the interactions among individuals exhibiting simple behaviours [5]. It is basic, for a robot in a swarm, to have at least simple capabilities such as movement or ambient perception. In order to achieve complex tasks, communication between the individuals is also a must.

Nowadays swarm research is a very active area. Nevertheless most of the approaches are focused on the software architecture only, and there is little research centered on hardware. In this paper we address the issue of developing a hardware interface that will allow the communication of microrobots in the I-Swarm colony.

The I-Swarm agents will consist of a stack of modules, each dedicated to a particular task such as power supply, locomotion, electronics, etc (**figure 1a**). The power supply module is composed by solar cells mounted on the robots and by a controlled illumination in the arena. In the locomotion module, movement is obtained by excitation of 3 piezoactuator legs. The communication module is a micro-optical system devoted to inter-robot communication, which has been presented in [6]. This module is also used for perception. All modules, i.e., powering system, locomotion module and communication module are controlled by the electronics module which is an ASIC. Specially for the communication the ASIC includes the complete transceiver.

The robots communicate via a short range IR link. Each one is provided with four pairs of one IR-LED and IR-photodiode assembled and wire-bonded along the borders of a thin squared substrate and encompassed by a mold-casted transparent polymer body (less than 1 mm thick) with a central pit with reflective 45°-sloped walls. This structure aims to out deflect the signals generated by the LEDs and to deflect towards the photodiodes the incoming signals (refer to **figure 1b**).

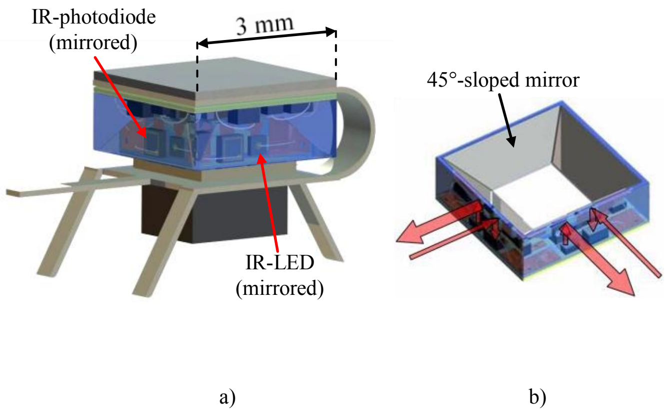

Figure 1: a) CAD drawing of Tentative Robot View; b) CAD drawing of the micro-optical system (size about 3× 3× 3 mm^3) to be turned upside down in the microrobot.

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The purpose of this paper is to present the IR-transceiver electronic interface of the robot. It has to deal with:

1) the non-homogeneous distribution of background as a consequence of the illumination used for the supply
2) the variations on the amplitude of the pulses received as a consequence of variations in the inter-robot distance or orientation.
3) the available energy in the system.

The transceiver is part of a SoC that contains an embedded 8051 processor and several controllers for the sensors and actuators of the robot. The SoC has been implemented in a 0.13µm ultra low power CMOS technology of STMicroelectronics. The paper is structured as follows: section II gives a short overview of the communication protocol. Section III focuses on the overall architecture of the transceiver. In sections IV and V the transmission and reception are treated. Then section VI focuses in detail on the test of the transceiver.

II. COMMUNICATION PROTOCOL

The communication protocol is simple in order not to demand excessive hardware and software resources and to be efficient in terms of power. The robot consumption is a critical issue because only 500 µW are available on board through a Ta capacitor connected to one of the solar cells. If the demand of current is too high, the capacitor discharges and the system fails.

In order to ensure a correct operation of the robot communications, the data are coded in short bursts of light pulses. **Figure 2** shows the three different bursts of light pulses used to code a start sequence, a logic ‘1’ and a logic ‘0’. The bursts are composed of one, two or three light pulses of length T_p and separated T_I seconds. The first pulse of two consecutive bursts must be separated T_{Bit} seconds. The T_p, T_I and T_{Bit} are adjustable within a wide range being the minimum values calculated in order not to discharge the capacitor.

The robot can send/receive frames of length between 1 and 32 bits long depending on the communication strategy of the swarm. The frames are composed of a start sequence and the message. No stop burst is required because the communication strategy is decided before programming the robots. Hence, the receiver counts the number of received bits to capture a frame.

The error encoding/detection as well as the data processing are done by software in the embedded 8051 microprocessor.

III. OVERALL ARCHITECTURE

The communication process is lead by the embedded processor of the SoC, which controls the transceiver. **Figure 3a** shows a scheme of the overall architecture of the transceiver. To send information via the TX channels, the 8051 writes the frames into an 8x32b internal buffer and then enables the transmission process. The four TX channels turn on/off the LEDs depending on the bit to send as commented in section II. The T_P, T_I and T_{Bit} as well as the length of the frame are stored into a register file.

The reception process is carried out by the Photodiode controller. An analog interface (section V) transforms the light bursts into voltage pulses that are processed by the four receiving channels RX. Received data are then explored to find a start burst. Finally, the incoming bits are written into the 8x32b buffer. When one full frame has been received, the RX channel sends an interrupt to the processor, which reads the frame and processes it.

The transceiver has a digital processing and analog front-end. The total power consumption of the analog interface is below 30 µW. Some modules have power-down capabilities. When the modules with power down capabilities are switched off the power consumption of the interface is below 10 nW. The analysis of the power consumption of the digital part is more difficult because some modules are shared with the locomotion, programming and processing functions of the robot. The total leakage of the digital part of the whole SoC is below 400 µW. When sending or receiving through one communication channel, the digital dynamic power consumption is below 25 µW.

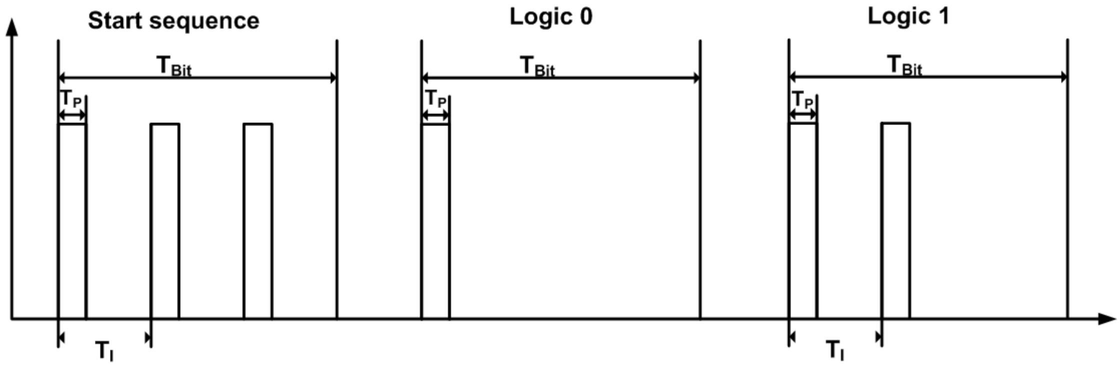

Figure 2: Basic coding of information.

IV. TRANSMISSION

The architecture of a TX channel is shown in **figure 3b**. The processor of the SoC can send information as explained above in two different ways. In one of the modes, the processor is able to directly drive the four LEDs. In this mode the processor has to control the T_p, T_I and T_{Bit} times. The control is done completely by software. The second mode was conceived because it was observed that sometimes a control only by software is too power demanding. In this mode it is possible to send the information bit by bit, i.e., the TX channels generate the sequence of light pulses to produce a '1', '0' or a start sequence.

The Bit to Light Burst Converter (BLBC), shown in **figure 3b**, receives the type of burst to be sent and generates the light pulses. T_P, T_I and T_{Bit} are generated with three internal counters. When the bit has been sent, the channel interrupts the processor to indicate that another bit or a synchronization sequence can be transmitted. Before being transmitted, a frame is stored in a buffer, serialized and passed to the BLBC.

The analog interface to transmit light pulses consists of a CMOS buffer driving a LED in series with a resistor. The CMOS buffer is physically situated in a digital output pad of the foundry libraries. In order to drive at 2V or higher (2V is required for the LEDs used), the IOs of the SoC are of 3.3V capabilities. The shifting from the 1.2V in the core area to the 3.3V in the IOs is done by the internal level shifters of the pads.

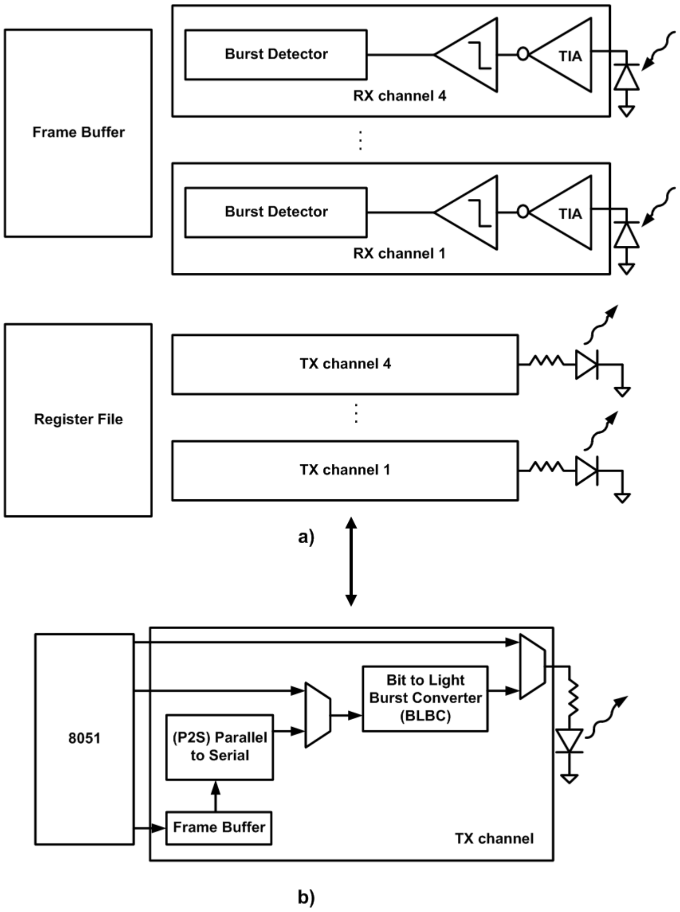

Figure 3: (a) Overall architecture of the transceiver. (b) TX channel architecture.

V. RECEPTION

In the reception process, an analog interface composed by a transimpedance amplifier (TIA) and a decision stage is used to transform the light bursts into voltage pulses that will be processed by the four receiving channels RX.

In wireless infrared communication systems the analog interface has to be carefully designed to manage the interferences induced by natural and artificial lights [7]. In the case of I-Swarm, the interferences are mainly produced by the illumination used for powering. This basically means that the background is not well defined.

In addition, depending on robot orientation and distance, the amplitude of the signal is also not very well defined.

To deal with these issues, a low power transimpedance amplifier (TIA) with programmable gain has been implemented as a front-end to do not saturate the input under all illumination conditions.

A similar solution has been already reported [8,9]. The difference here is that the analog interface is programmable by the embedded processor in order to manage different backgrounds and signals. In order to administrate the available power the circuits can be switched-off.

Figure 4 shows the schematic of the TIA amplifier. It is composed of the amplifier presented in **figure 4** and of a programmable feedback resistor implemented with pMOS transistors (R1-R8 nMOS switches). The basic structure of the CMOS amplifier (**figure 4**) consists of an inverter (M1-M2) followed by shunt feedback transistors (M3, M4) that symmetrically broad the range of input voltages over which the following stage has gain.

The amplifier is composed of three of these basic structures and has an open loop gain of 39.6dB and a bandwidth of 860 kHz. The gain of each basic stage is determined by the ratio W/L of the transistors M1-M4.

The gain of the TIA amplifier is selected by programming the R1 to R8 nMOS switches. The analog interface can be able to afford backgrounds from nA to µA.

The pulses generated by the photodiode are already superimposed to the background, after the amplification stage. In order to discriminate pulses and give a logic level to the digital electronics of the transceiver, a decision stage is connected to the output of the TIA. The scheme is shown in **figure 4**.

The input stage of the comparator is a CMOS inverter that fixes the minimum reference. By activating M32-M36 pMOS transistor, the impedance between Vdd and the output of the first CMOS inverter is changed, and the commutation point is increased. A total of 2^5 possible reference values have been implemented with transistors M32-M36. Nevertheless, for a simple control only 5 possibilities will be used.

After the analog interface, a digital filter has been added to filter the high frequency noise.

Once the analog interface has transformed the light bursts into voltage pulses, the RX channels explore the received data for a known burst sequence. When a valid start burst is received, the receiver checks the T_p, T_I and T_{Bit} of each incoming bit. If one of these timings is not correct, the bit as well as the rest of the frame received is discarded and the receiver starts looking again for a new frame. This avoids collision of information between robots.

Actually, the process is slightly more complicated because of the clock variations from chip to chip. As the process of measuring the duration of the light pulses is locally done with a 10b counter and because of the dispersion observed in the frequency of the clock from chip to chip, it is required to allow for small variations of the counted length around the expected local duration.

To manage the clock frequency dispersion and the width variation of the pulses, the receivers must accept light pulses of a length within a tolerance window. In this way, the reception channel has three programmable windows detectors that measure T_p, T_I and T_{Bit}. If the measured values are within T_{min}, T_{max}, T_{Imin}, T_{Imax}, T_{Bitmin} and T_{Bitmax} respectively the data are accepted and otherwise are rejected (**figure 5**).

VI. TEST

Before doing experiments on the transceiver, the optical-module has to be tested to characterize its behavior and make consequently the minimum error in the test of the transceiver.

As was explained in Section I, the optical-module is composed of one IR-photodiode and of one IR-LED, and each pair is assembled on each of the four sides of the robot.

The optical-module has been tested with an external TIA with a feedback resistor of 14.1MΩ. 50000 pulses of light have been sent by the IR-LED for different distance between the IR-LED and the IR-photodiode. The obtained results are plotted in **figure 6** and **figure 7**. These results are good because similar results are obtained for different angle tests.

By knowing that the feedback resistor of the TIA of the ASIC is three times smaller than the feedback resistor used for the external TIA, the approach of testing the transceiver on a distance range three times smaller has been pursued.

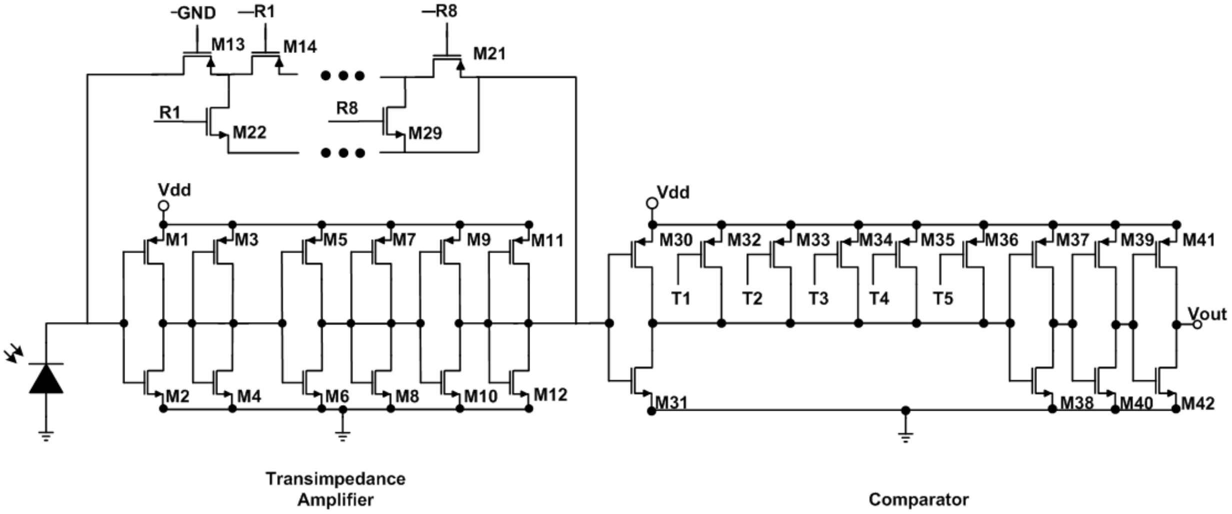

Figure 4: Schematic of the transimpedance amplifier and the comparator.

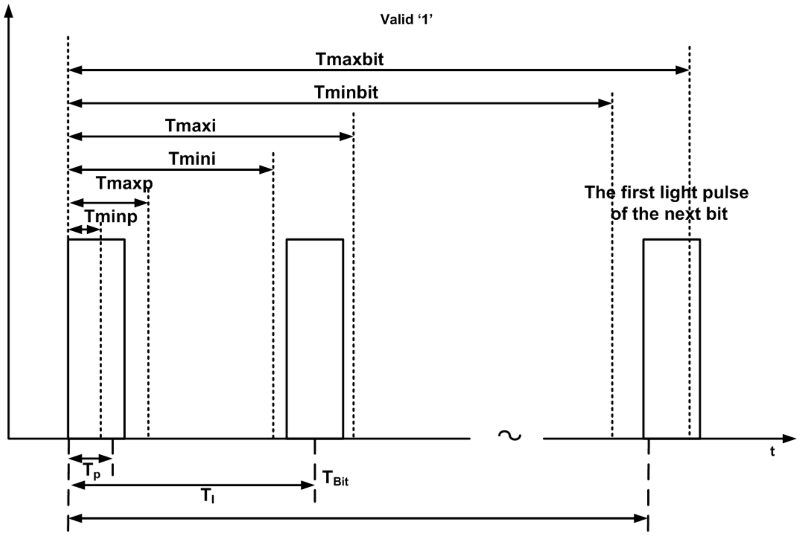

Figure 5: Illustration of the windowing used to avoid the effects of variation.

Finally, two tests have been done for the transceiver module. A first basic test for the transceiver has been performed. For the test we have used the micromirror structure with the LEDs and the photodiodes assembled, an initial prototype of the ASIC with the analog part of the transceiver and a DSP Stratix development board of Altera where we synthetized all the digital part of the SoC. The procedure for testing consisted in sending frames with the Altera board and use the synthetized SoC, and the ASIC to reconstruct the frames. The process is exactly the same as it was performed by two robots. **Figure 8** shows an image of the setup done for the test. In **Figure 9** it is shown the communication process between the two robots done in this way. Signal D4LEDNIO shows a coded frame of 8 bits sent by one robot. This signal is received (D2-FILTRE), decoded by the other robot and sent again (signal D10-LEDISW).

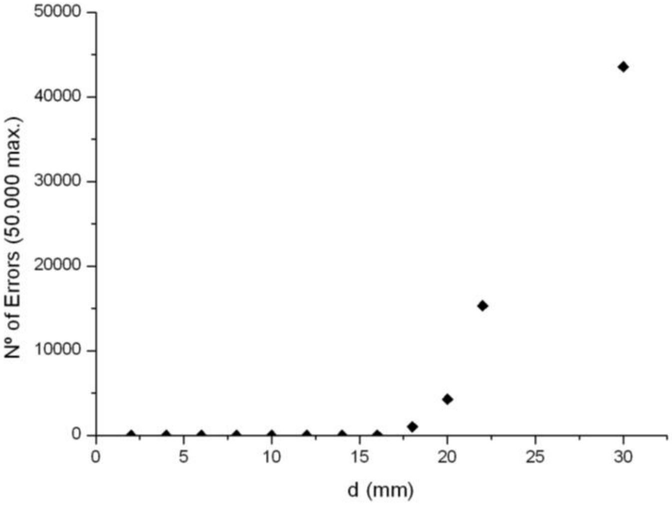

Figure 6: Nº of errors for each different distance, when the IR-LED and IR-photodiode are face off.

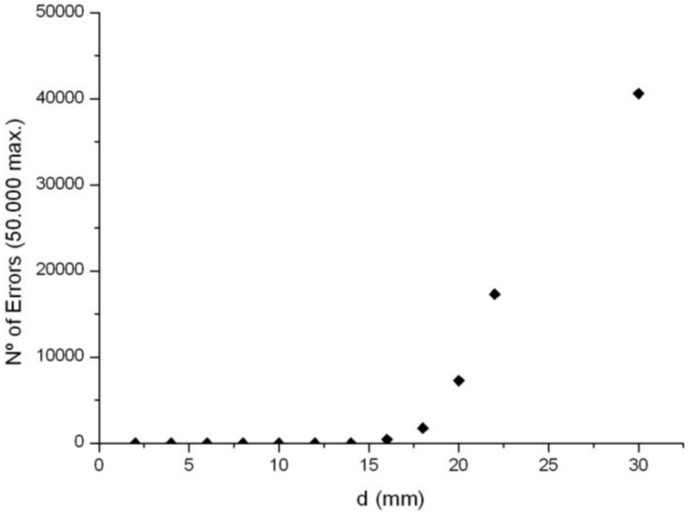

Figure 7: Nº of errors for each different distance, when the IR-LED and IR-photodiode are communicating in an angle of 45º.

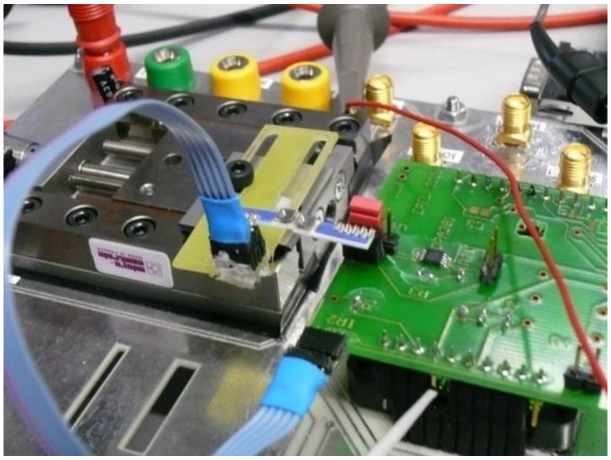

Figure 8: Image of the two robots (center of the image).

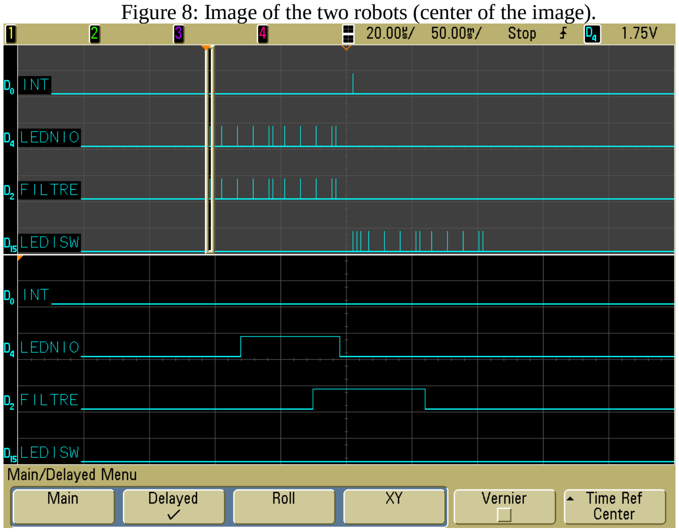

Fig. 9: Experimental results for the communication process between two robots.

Another test has been done with the goal to demonstrate the utility of the programmable windows and to prove the maximum distance, between robots, that could be achieved while they are communicating. For the test, the width of the sent pulses was 60 µs (T_p) and the pulses have been separated 3 ms (T_I). To achieve maximum distance, the TIA has been programmed with the maximum gain. This means, that the robots could be able to communicate until this maximum distance by changing the gain of the TIA. **Figure 10** shows the range of distances in which it is possible to communicate (shadowed area). In this test, the T_p window is chosen between 50 µs and 70 µs. In addition, the threshold values of the comparator are chosen to cover the full range, and go from the maximum threshold (value 7 in decimal) to the minimum (value 1 in decimal).

This last test has been repeated for a window from 40 µs to 80 µs. The results are plotted in **figure 11**. In this case, the maximum distance for communications is achieved, and is of 4.3 mm. Out of the shadowed area, communication is even possible, but with some errors. As commented in Section II, if only one bit is not within the window the entire frame is discarded, and this implies that the frame error increases rapidly with the distance between the robots.

Comparing the results for the two windowing tests, it can be seen that when wider windows are used, the distance range of communication is increased. The reason of that are the rise and fall times of the received signals. As it is illustrated in **figure 12**, for different threshold values of the comparator, different widths of the received pulses are obtained. The amplitude of the generated photocurrent depends on the distance between the led and the photodiode and the rise and fall time are the same for all the pulses. So, for different amplitudes and the same threshold, the width of the pulse after the comparator is different. As the wider windows allow the reception of wider pulses, the range is increased.

Finally, it can be seen that the dependency between distance and the threshold of the comparator is non-linear. The loss of linearity occurs when the threshold descends to the minimum value. This is due to the first stage of the comparator. When any PMOS (M32-M36, see **figure 4**) is active, the gain of the amplifier decreases and the linear range of this amplifier is increased. Howere, when the minimum threshold value is fixed, the first stage of the comparator is just an inverter, with high gain and low linear range (**figure 13**). For this reason, the dependency between distance and the threshold of the comparator is linear from higher thresholds to threshold values near to the minimum.

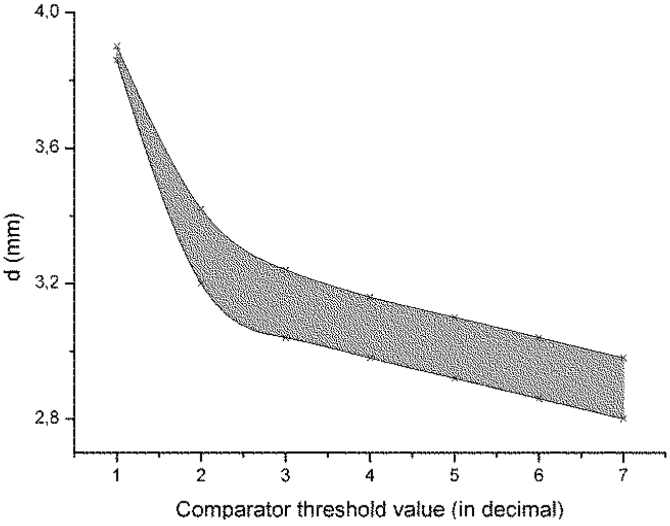

Fig. 10: Experimental results for the communication process between two robots (with a window from 50 to 70 µs). The shadowed area shows the distance range not to lose frames.

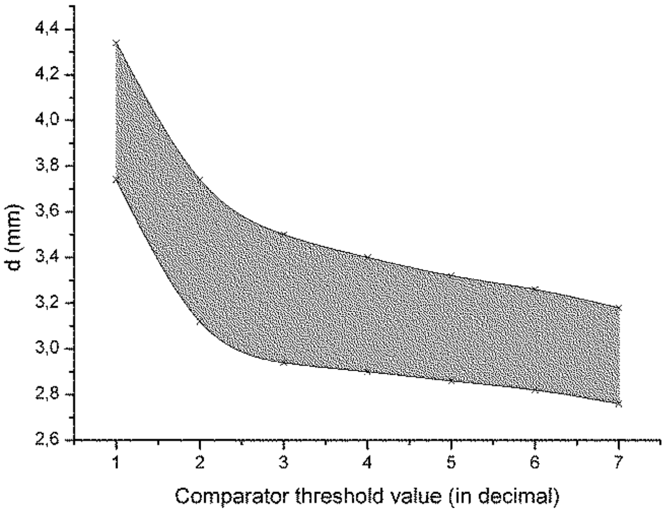

Fig. 11: Experimental results for the communication process between two robots (with a window from 40 to 80 µs). The shadowed area shows the distance range not to lose frames.

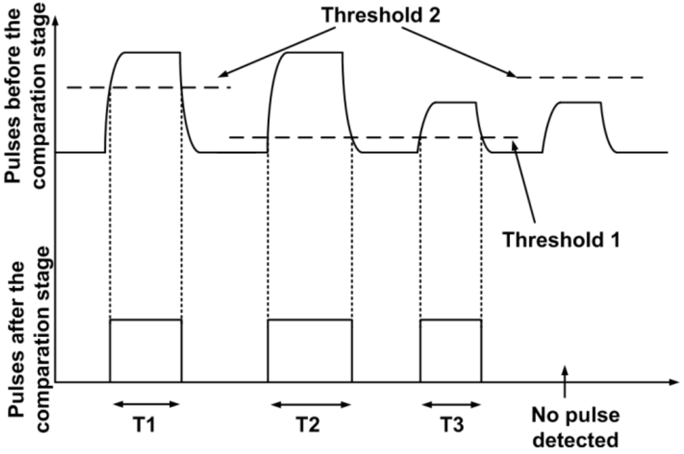

Fig. 12: Example of the different widths of the pulses received when the threshold of the comparator is changed.

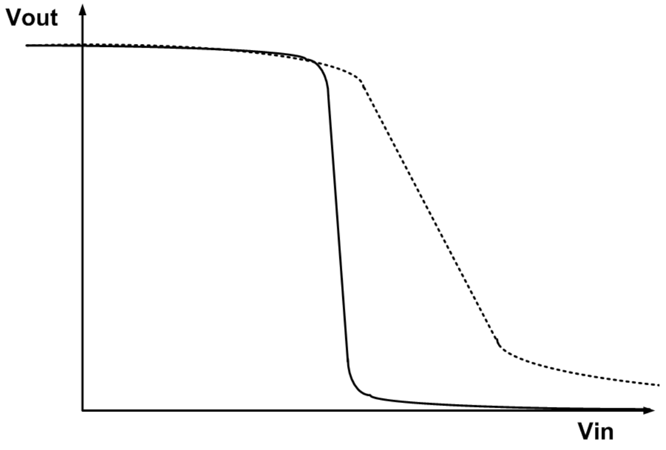

Fig. 13: Example of the voltage response variations for the first stage of the comparator when different thresholds have been fixed. Continuous line represents the voltage response when the minimum threshold is fixed. Discontinuous line represents the voltage response when a higher threshold than before is fixed (one or more of the M3-M7 PMOS are active).

VII. CONCLUSIONS

In this work we have described the transceiver designed for the optical communication of a colony of robots in a swarm at very low rate. Taking into account the mm^3 size and the low energy available, care has been taken in the power consumption and especially in the case of the design of the communication module. This impacts the design of the protocol and of the circuits. In order to deal with the small area available the approach has been to design the transceiver as simple as possible. Despite the simplicity, the transceiver solves the difficulties related to a not well controlled ambient light and even the variations of local frequency of the clock among the robots in the colony.

In order to satisfy these very hard conditions imposed by the development of integrated circuits for microrobotics, i.e., basically a very small area and very low power consumption, the approach followed has been to design it as simple as possible. Despite the simplicity, the transceiver solves the difficulties related to a not well controlled ambient light and even the variations of local frequency of the clock among the robots in the colony.

As can be seen in the Test Section, the maximum distance achieved during the communication of two robots is of 4.3 mm. This seems to be a not very good result, but by knowing that the total area of one robot is 9 mm^2, the total area around the robot where the communication is possible is 12 times bigger. Furthermore, the distance range can be easily enlarged by increasing the feedback resistor of the TIA in the ASIC.

In addition, with this communication strategy, no error bits are received. If the robots are able to communicate, the entire frame will be received, or no frame will be received, but never will be an error bit.

Finally, with this interface the robots are endowed with inter-robot communication capability. In the framework of swarm and sensor networks research it allows, among others, the possibility to explore communication routing strategies or observe the evolution of a swarm by direct interaction between individuals in real time.

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