A Low Power Optical Interface for Inter-Robot Communication in a Swarm of Microrobots

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Abstract: - A low power optical communication interface is presented. It has been designed for an optical link between a thousand of microrobotic units in a swarm. The robots, of mm^3-size, will be deployed in an arena of A4 paper size with controlled illumination conditions. The communication between robots is done via IR light. The interface deals with variations of the IR background light from point to point in the arena, with robot orientation and distance, i.e., the amplitude of the signal to be detected, and with inter-robot interferences.

Key-Words: - swarm, robots, transimpedance, amplifier, comparator, communications, low power

1 Introduction

Miniaturized robotic systems open new challenges not only in mobile robotics but also in many connected areas such as sensor systems, locomotion, energy supplying, communications and so on [1]. Current state of the art of miniaturized robots is in 2x2x2 mm 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 behavior in the colony.

In a swarm, collective behavior emerges from the interactions among individuals exhibiting simple behavior [3]. It is basic, for a robot in a swarm, to at least have 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.

In I-Swarm, the autonomy of the robots is assured with solar cells mounted on the robots and by a controlled illumination in the arena. Movement is obtained by excitation of 3 piezoactuator legs. The robots communicate via a short range IR link. Each one is provided of four pairs of one IR-LED and IR-photodiode (figure 1). Each pair is assembled on one the four sides of the robot to sense in all directions at the same time. A top mirror reflects the emitted light from the LEDs in a direction parallel to the floor.

The purpose of this paper is to present the IR transceiver 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 0.13um ultra low power CMOS technology of STMicroelectronics. The paper is structured as follows: section 2 gives a short overview of the communication protocol. Section 3 focuses on the overall architecture of the transceiver. In sections 4 and 5 the transmission and reception are treated. Then section 6 focuses in detail on the analog interface of the reception.

2 Communication protocol

The communication protocol is simple in order to do not 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.

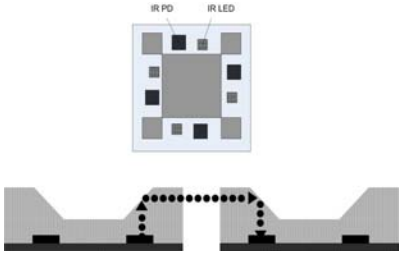

Figure 1: Top and side view of the micromirror and the LED/photodiode structure. The optical link is shown for two robots.

If the demand of current is too high, the capacitor discharges and the system fails.

In order to assure a correct operation of the robot communications, the data has been 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 to not discharge the capacitor.

The robot can send/receive frames of length between 4 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. So 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.

3 Overall architecture

The communication process is lead by the embedded processor of the SoC. It controls the transceiver. Figure 3 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.

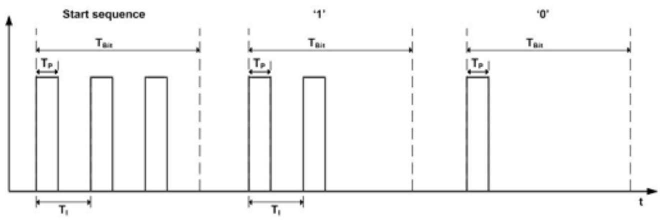

Figure 2: Basic coding of information

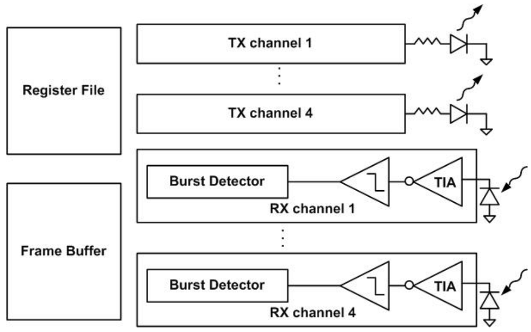

Figure 3: Overall architecture of the transceiver

The four TX channels turn on/off the LEDs depending on the bit to send as commented in section 2. 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 6) transforms the light bursts into voltage pulses that are processed by the four receiving channels RX. The received data is 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 interruption to the processor, that reads the frame and processes it.

4 Transmission

The architecture of a TX channel is shown in figure 4. 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 thought because it was observed that sometimes a control by only 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 BLBC (figure 4) receives the type of burst to be sent and generates the burst 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. To send a frame, it is stored in a buffer, serialized and passed to the BLBC.

5 Reception

The RX channels are always waiting for known burst sequences. When a valid start burst is received, the receiver checks the T_p, T_I and T_{Bit} of each incoming bit.

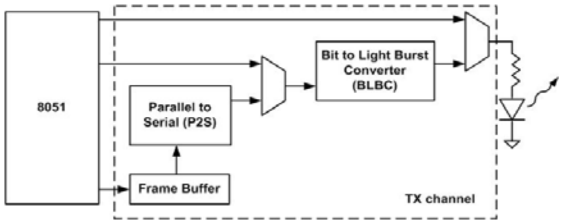

Figure 4: TX channel architecture

If one these times are 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, the receivers must accept light pulses of a length within a window. In this way, the reception channel has three 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).

6 Analog interface

The analog interface to transmit light pulses consists in 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.

In wireless infrared communication systems the reception interface has to be carefully designed to manage the interferences induced by natural and artificial lights [4]. 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.

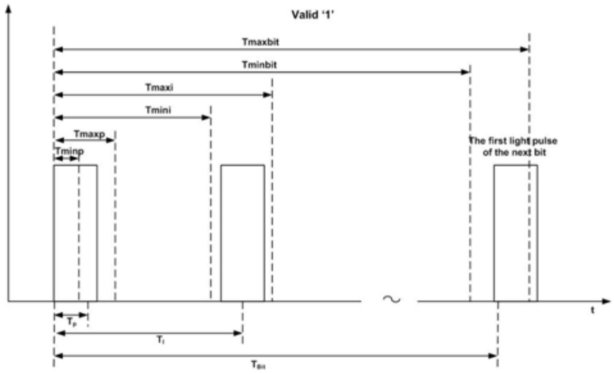

Figure 5: Illustration of the windowing used to avoid the effects of variation of the local frequency.

A similar solution has been already reported [5,6]. 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 6a shows the scheme of the TIA amplifier. It is composed by the amplifier presented in figure 6b and by a programmable feedback resistor done with pMOS transistors (R1-R8 nMOS switches). The basic structure of the CMOS amplifier (figure 6b) 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 860kHz. The gain of each basic stage is determined by the ration 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 uA.

After the amplification stage, the pulses generated by the photodiode will be superimposed to the background. In order to discriminate such 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 7.

The input stage of the comparator is a CMOS inverter that fixes the minimum reference. By activating M3-M7 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 M3-M7. Nevertheless, for a simple control only 5 possibilities will be used.

(a)

(b)

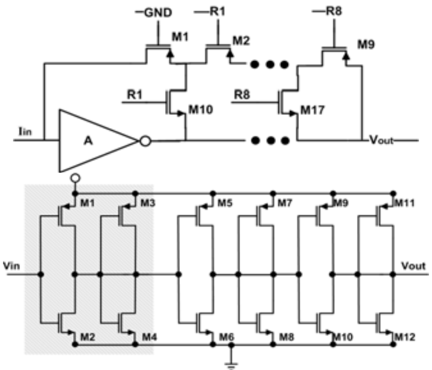

Figure 6: (a) Schematic of the transimpedance amplifier (b) Simplified (power-down transistor is not shown) transistor level schematic of the amplifier of the TIA.

7 Test

Figure 8 shows the communication process between two robots. Signal D4 shows a coded frame of 8 bits sent by one robot. This signal is received (D5), decoded by another robot and sent again (signal D3).

This is a test of the complete comunication process and shows that the analog interfaces, the transmision and reception channels and, the processing works properly.

8 Conclusions

We have described the transceiver designed for the optical communication of a colony of robots in a swarm at very low rate. In order to satisfy the 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. 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 tool to explore communication routing strategies or observe the evolution of a swarm by direct interaction between individuals in real time.

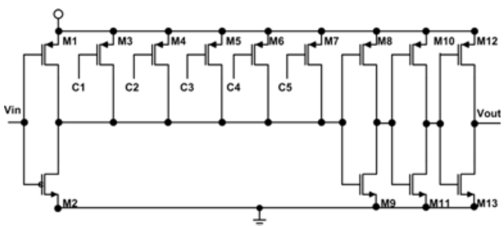

Figure 7: Simplified (power-down transistor is not shown) transistor level schematic of the decision circuit.

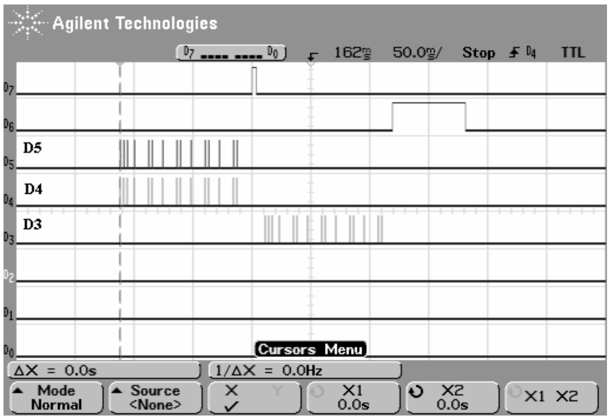

Fig. 8: Experimental results for the communication process between two robots

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