A Self-Reconfigurable Communication Network for Modular Robots

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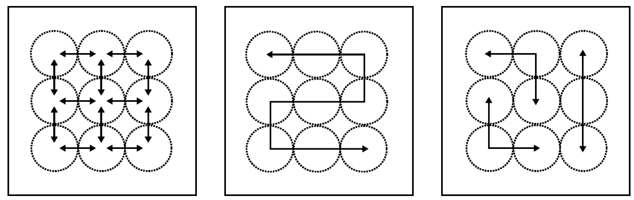
***Abstract*—We present a novel hybrid communication system for modular robots, based on inter-module buses that can connect on-demand to form arbitrary network topologies.**

In addition to describing the implementation of this hybrid communication system, we analyse transfer rates and reliability, validating the results using a Spice [1] simulation and a proof-of-concept experiment performed on a hardware prototype.

Thus, we find the system is fast, since it has a potential to provide a maximum transfer rate of 9.9Mbps divided by the maximum bus length measured in meters, with buses as large as 256 modules. The system is also found to be small in size, power saving and reliable. These features, in combination with its flexibility, make hybrid communication suitable for modular robots.



(a) Local Buses. (b) Global Bus. (c) Hybrid Buses.

Fig. 1. Different kinds of communication buses within a modular robotic system. Here, modules are represented by circles and buses by arrows. In (a), every module communicates only with the adjacent neighbour modules using local buses. In (b), all the modules of the system communicate between each other through a common channel, a global bus. Finally, in (c), several non-global channels, hybrid buses, enable the communication between non-adjacent modules within the system. The global bus of (b), can be seen as an special case of hybrid bus.

I. Introduction

Modular robots are robots built from modules. The design of these systems is limited to homogeneous or heterogeneous modules, with basic functionality, which are able to combine into more complex entities. Thus, instead of designing a new robot for each task, a new suitable structure can be assembled from the available modules [1] [2].

Communication is central to modular robots. Local communication is used to figure out the topology of the robot and to coordinate tasks involving just local information [3]. On the other hand, global communication is needed for tasks which may require time critical coordination between distant modules of the system.

The hybrid communication approach provides a solution that is able to reconfigure the communication topology from small and local buses to long and more global buses, here called hybrid buses. The last is done on-demand, using the same buses and hardware, and maintaining the local transfer rates after the new topology is established. Figure 1 shows three examples of network topologies that hybrid communication can provide [4].

Theoretical analysis indicates that the maximum transfer rates of the hybrid communication approach could be around 9.9Mbps divided by the maximum length of the hybrid buses measured in meters, with buses as large as 256 modules. Besides, the system is flexible, small in size, power efficient, and reliable.

[1]Spice is a general purpose circuit simulator that allows to check integrity of circuit designs and to predict circuit behaviour.

This paper introduces the hybrid communication approach, beginning with Section III, which describes the requirements, design and implementation details of the communication system. Then, Section IV presents Odin, a novel modular robotic system with a concrete implementation of the hybrid communication approach. The paper continues with Section V, which analyses performance based on transfer rates: in general for any hybrid communication system and specifically for Odin. Afterwards, Section VI validates the results of the performance analysis carried out on Odin, using a Spice simulation, and presents a proof-of-concept experiment performed on a hardware prototype of the same system. Then, in Sections VII and VIII, we discuss potential issues that can appear when implementing the hybrid approach and the future direction of our work. The paper finishes with Section IX, where we conclude that the hybrid communication approach is suitable for modular robots.

II. Related Work

The trade-off between local and global communication in modular robotic systems has previously been pointed out by several authors [4] [5]. Thus, designers of modular robots have followed many approaches for taking advantage of both communication modalities.

A combination of two global communication mechanisms is used in the CEBOT self-reconfigurable robot [6]: serial wireless for self-reconfiguration (1Kbps) and parallel wired for coordination once connected (8 channels at 1Kbps). While

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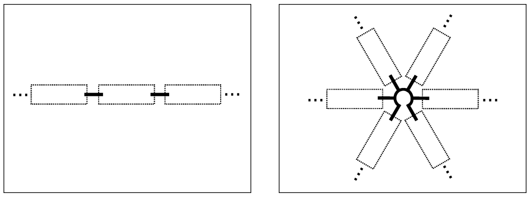


(a) One-to-one local buses. (b) Many-to-many local bus.

Fig. 2. Different types of local buses. Here, modules are represented by rectangles and buses by lines. In (a), the local buses connect two adjacent modules (neighbour-to neighbour communication). An example of this kind of system is homogeneous modular chain-type self-reconfigurable robots. In (b), a local bus connects many adjacent modules. In this kind of system, the local buses may be implemented outside the modules, within special types of modules acting as joints. An example of this kind of system is heterogeneous modular lattice-type self-reconfigurable robots.

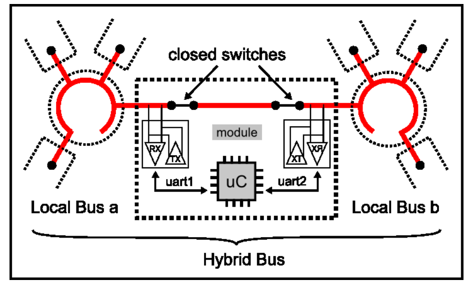


Fig. 3. A module merging two local buses into a more global bus (hybrid bus) by closing its internal switches. If another adjacent module also closes its switches, the hybrid bus grows. When the hybrid bus is able to communicate all the modules within the system, it becomes a global bus. Here, the buses are represented by a single line, in spite of they are conformed by two wires.

it gives the CEBOT system two modalities of global communication, it does not allow modules to communicate locally.

Other designers have opted for implementing only local communication in their systems. CONRO [7] and ATRON [8] self-reconfigurable robots, have both infrared local communication at a transfer rate of 9600bps. For the ATRON, the main problem with this approach is the crosstalk between different modules.

Wireless communication is also used in the YAMOR [9] reconfigurable robot, where a complete bluetooth interface is fitted within large modules. Nevertheless, this kind of communication does not allow the modules to determine the physical location of their neighbours without using external sensors.

An alternative implementation of both communication modalities at once, was made in the M-TRAN II [10] self-reconfigurable robot. This system provides local (4800bps) and global (39Kbps) communication channels, by using three separated media and microcontrollers. In the M-TRAN II system, the dynamic topology of the global network (motivating the exclusion of termination impedance) is the main constraint for the transfer rates.

We believe the present work improves the communication capabilities of modular robotic systems, by allowing the implementation of both communication modalities at once: with high transfer rates, requiring only one type of communication hardware, using wired media, and requiring limited space.

III. The Hybrid Communication Approach

In a communication system for modular robots, a *local bus* provides a medium for exchanging messages between neighbor modules, whereas a *global bus* provides a medium for exchanging messages between all the modules in the system. Nevertheless, in the the context of the hybrid communication system, there is a third definition: a *hybrid bus* provides a medium for exchanging messages between non-neighbors or distant modules in the system (see Fig. 1).

A. Requirements

The main purpose for a hybrid communication system is to provide local, hybrid and global communication buses, all of them allowing high transfer rates. Further, the system must be small in size, scalable, power saving for the sake of autonomy and reliable with regards to the noise ratio supported by the signals; which are the minimal set of features required by a modular robotic system.

B. Design

The idea behind the hybrid communication approach is to have fixed local buses. Then, on-demand, hybrid buses can be created by merging two or more local buses. If the hybrid bus is connecting all the modules in the system, it is a global bus.

1) Local Buses: The local buses are implemented as serial communication buses. Hence, modules must have a dedicated transceiver per local bus being accessed. Fig. 2 shows two examples of local buses, while Fig. 3 shows internal details of a module accessing two local buses.

2) Hybrid and Global Buses - Switching: For merging local buses, the modules must have an internal bus which can be attached to all the local buses being accessed. Thus, the internal bus is able to combine different channels into a common hybrid bus. The attachment can be achieved by using switching technology. Fig. 3 shows an example of module merging its local buses.

3) Termination Impedance: The termination impedance is crucial for achieving high transfer rates, without decreasing the reliability of the communication system [11]. As the local buses are to be merged in a more global medium, the ideal pure resistive termination overloads the transceivers acting as drivers as soon as more than two local buses are merged [12]. Therefore, and conforming to the power saving requirement, the chosen termination impedance for the hybrid communication approach is an AC termination [13]. Fig 4 shows a local bus terminated with an AC termination.

C. Implementation

1) Local Buses: For the sake of transmission rates, robustness, and transmission distances, the physical layer protocol used is RS485. As RS485 transceivers are characterized by unit loads, in the sense of electrical power consumed from the signal being transmitted, the transceivers included in the modules should have $1/8$ of load, to create hybrid buses as large as 256 modules.

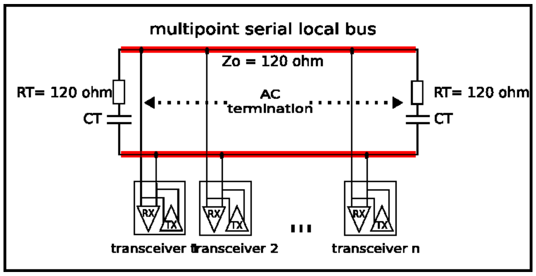


Fig. 4. A local bus implemented using a transmission line with characteristic impedance $Z_0 = 120\Omega$. The AC termination consist of one resistor R_T in series with one capacitor C_T. R_T matches the characteristic impedance of the line, $Z_0 = 120\Omega$, and C_T is dependant on the expected maximum length of the hybrid buses. The AC termination is a balance between signal quality, power requirement, and transmission rates.

2) Hybrid and Global Buses - Switching: Considering the RS485 wiring guidelines [14], the cables used to implement local and hybrid buses (the internal bus within the modules), should be twisted pair and have a characteristic impedance of 120Ω. Moreover, for keeping low power consumption and high side switching capabilities, the buses should be extended with analog switches. Hence, the closed resistance should be as low as possible, then not to have important reflections nor voltage drops across the hybrid buses. Finally, the switches should be located at the RS485 side of the transceivers (not the UART side), as shown in Fig. 3.

3) Termination Impedance: When terminating a transmission line with an AC termination, two components are placed in series at the termination impedance: one resistor, R_T, and one capacitor, C_T (see Fig. 4).

R_T matches the characteristic impedance of the line (120Ω), and C_T is selected to be less or equal to the round trip delay of the cable divided by the characteristic impedance [13]. The round trip delay is defined as twice the time required for a signal to travel until the end of a line.

Thus, C_T is calculated as:

$$C_T = \frac{1}{120}\,\frac{2\,l_{cable\_max}}{0.66\,c} \tag{1}$$

where c represents the speed of light, $0.66\,c$ is the typical propagation velocity of a twisted pair cable, and l_{cable_max} is the maximum expected length of the hybrid buses.

Ideally, there should be just two AC terminations per local bus: one at each end. Therefore, in systems like Fig. 2a, the termination could be embedded within the modules; while in systems like Fig. 2b, the termination should be placed someway outside the modules.

IV. The Odin Modular Robot

Odin is a reconfigurable modular robot, which is made of heterogeneous modules (links) and joints (balls). These components can be locked together by a flexible connector-socket mechanism, which is also able to forward electrical connections [15].

The modules embed the connectors, while the joints embed the sockets. Further, a module connects two joints (one per end), while a joint can be connected to a maximum of 12 modules. The position of the sockets in the joints arranges the modules into cubic closed packing lattice (CCP). Fig. 5 shows the first prototype of Odin.

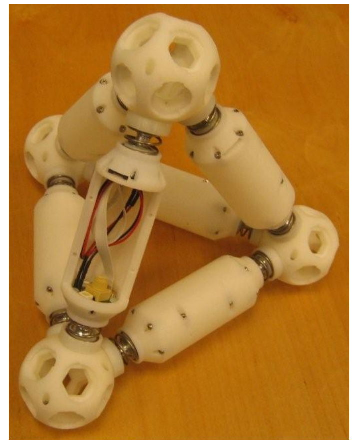


Fig. 5. First prototype of the novel Odin modular robot. In the Odin robot, modules are connected to joints (balls) to form a robot configuration. Here we can see 4 joints shaping 6 modules into a tetrahedron, a sub arrangement of the cubic close packing lattice (CCP). The joints wrap local buses, the modules embed the extending bus, and the connectors forward the electrical connections. The diameter of the joints is 50mm and the length of the modules is 110mm.

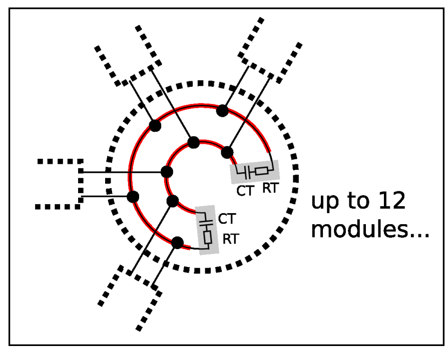


Fig. 6. Local buses of Odin. One AC termination is placed at each end of the bus. The maximum number of modules to be connected to the local bus is 12, and each module contributes 1/8 of load to the bus. The value of the capacitor C_T of the AC termination is determined by the maximum expected length of the hybrid buses (not the length of the local buses).

A. Odin's Hybrid Approach Implementation

In the case of Odin, the local buses are implemented outside the modules, within the joints. As recommended in Section III, two AC terminations are placed per local bus, one at each end. Fig. 6 depicts the implementation of the local buses within the joints of Odin.

The maximum numbers of modules to be connected to each local bus is 12. Further, two transceivers are implemented per module, one at each end. Finally, the stub of the transceivers is forwarded from the modules to the joints through the connectors. Fig. 3 depicts the interior of an Odin module connecting two joints.

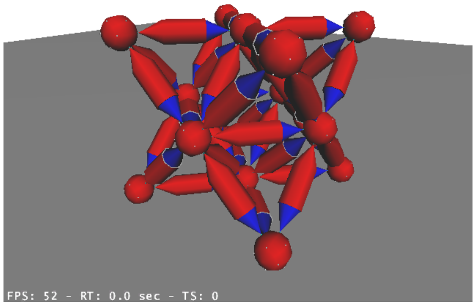


Fig. 7. CCP lattice arrangement of Odin. If we continue expanding the size of the arrangement, by attaching more modules to the joints, the average number of modules per joints will converge to 12. The image was taken from the USSR simulator (Unified Simulator for Self-Reconfigurable Robots), which includes a model of the Odin system.

B. CCP: The Lattice of Odin

A lattice is a mathematical concept used in crystallography, the science that describes the ways in which atoms and molecules are arranged in crystals [16]. As lattice-type modular robots are inspired by the discrete arrangement of atoms, the same concept is used to describe their configurations. Odin is a heterogeneous modular CCP lattice robot.

CCP lattice means that, if we imagine a 3D space grid, points are placed at each corner of a cube and also at every center of the six faces enclosing it. In crystals, these points are coincident with the location of atoms, but in Odin, they are coincident with the centers of joints. Moreover, the connectivity of atoms touching other atoms in crystals is represented by modules in Odin. Fig. 7 depicts the CCP lattice arrangement of Odin.

In this section we perform a light analysis of the lattice of Odin, which will help us to estimate some parameters required for the next sections.

1) Number of joints versus size of the structure: Assuming a cubic expansion of the structure of Odin, when increasing the number of modules and joints (e.g. Fig. 7); we can find a relation between a_n, the normalized edge length of a cube enclosing the structure, and the number of joints composing the system.

To begin, we define imaginary spheres concentric with the joints within the volume of the structure. These virtual spheres have a volume $V_b = \frac{4\pi}{3}\left(\frac{m}{2}\right)^3$, where m is the distance between the centers of two adjacent joints in the system. Thus, we calculate the number of joints, b_V, packed within the volume of the cube, $V = a^3$, as:

$$b_V = \frac{0.7405a^3}{V_b} = 0.7405\frac{6}{\pi}\left(\frac{a}{m}\right)^3 = 0.7405\,\frac{6}{\pi}\,{a_n}^3 \qquad (2)$$

where the factor 0.7405 represents the spheres' packing efficiency in the CCP lattice [16].

2) Number of modules versus size of the structure: CCP indicates the number of modules per joint is 12 when the joints are located within the volume of the structure. Thus, the total number of modules composing the system, N, can be approximated as:

$$N = b_V\,\frac{12}{2} = 0.7405\,\frac{6^2}{\pi}\,{a_n}^3 \qquad (3)$$

3) Average number of modules per joint versus size of the structure: A consequence of the cubic and quadratic nature of volume and surface, respectively, is that the ratio $r = \frac{volume}{surface}$ grows proportionally to the size of the structure [17]. Thus, we can approximate the average number of modules per joint, n, as:

$$n = 12\frac{V_n}{S_n + V_n} = 12\frac{a_n}{6 + a_n} \qquad (4)$$

where the term $V_n/(S_n + V_n)$ is the proportion of volume of the structure. Here we can see that when a_n approaches infinite (pure volume), n tends to 12 [17].

4) Hybrid buses length versus size of the structure: Assuming that each module merging local buses attaches $n - 1$ modules to the hybrid bus (with the exception of the first one), the length of a hybrid bus communicating N modules can be approximated as:

$$l = \frac{N}{n-1} - 1 \qquad (5)$$

Note that l is not the physical length of the cable, but the number of modules acting as bridges between local buses (internal switches closed).

5) Discussion about structural analysis: We have ignored the contribution of modules and joints placed in the surface of the structure. Nevertheless, the previous equations are valuable estimations of n and l when the number of modules, N, grows; which is specially useful in a system aiming for scalability.

C. Maximum hybrid bus length l_{max}

From section III, we know the maximum number of modules we can communicate with a single hybrid bus is 256. Therefore, by combining the equations (3), (4) and (5), we can get an estimation of the maximum length of the hybrid buses: $l_{max} \approx 80$ closed modules. The last can be translated into a physical cable length of:

$$l_{cable\_max} = l_{max}0.2m = 16m \qquad (6)$$

where $0.2m$ is the length of the bridge cable embedded on each module of Odin (worse case scenario).

Finally, the assumption of a maximum of 256 modules connected to a hybrid bus must be handled with care. If two transceivers are implemented per module, $2/8$ instead of $1/8$ of load could be attached to the bus. Therefore, the hardware should be able to disable one of the transceivers, when the module closes its switches or when it is communicating through the same hybrid bus on both ends.

D. Value of C_T for Odin

As we know the maximum expected length of the hybrid buses for Odin, l_{cable_max}, we can now calculate the value of C_T; the capacitor to be used in the AC termination of the local buses. Thus:

$$C_T = \frac{1}{120}\,\frac{2 * 16}{0.66\,c} \approx 1nF \tag{7}$$

V. Performance Analysis

The transfer rates affect the overall performance of a system. Instead of constraining the maximum length of the extended buses to be created by the hybrid communication approach, we are more interested in determining the maximum transfer rates we are able to communicate at, when having a defined structure.

A. Maximum Transfer Rate for A System In General

For digital signals, a rule of thumb of AC terminated transmission lines says that: the time constant $\tau = R_T\,C_T$ should be less than or equal to 10% of the bit width [13]. Therefore, the maximum transfer rate of the hybrid communication approach, tr_{max}, is determined by:

$$tr_{max} = \frac{1}{10}\,\frac{1}{120\,C_T} = \frac{0.66\,c}{20\,l_{cable\_max}}\,bps$$
$$= \frac{9.9}{l_{cable\_max}}\,Mbps \tag{8}$$

B. Maximum Transfer Rate for Odin

Following the last section, we can now calculate the maximum transfer rate, tr_{max_odin}, to be achieved by the Odin modular robot:

$$tr_{max\_odin} = \frac{0.66\,c}{20 * 16} \approx 620\,Kbps \tag{9}$$

C. Consequences of Bad Topology

The hybrid buses created by the communication approach may present a topology similar to the bus at Fig. 8. There, we can see that one transceiver is driving more than one local bus, which is discouraged by the RS485 wiring guidelines [14].

Nonetheless, those recommendations emphasize the load applied to the drivers, which is properly avoided by the AC terminations; and the reflexions generated in the connections points, which should be minimal if the switches extending the local buses have very small resistance.

VI. Experiments

By having a concrete implementation of the hybrid communication approach in the Odin modular robot, we are able to perform simulations and experiments. The last allow us to validate the expected transfer rates and the capabilities of the communication system.

A. Spice Simulation

1) Settings: The simulations were performed in the Spice like simulator, LTSpice[2], by using trivial components. The

[2]http://www.linear.com

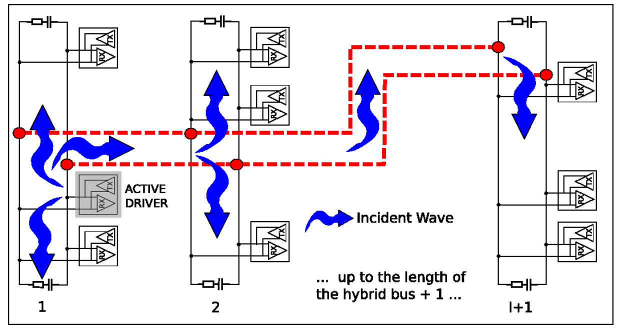


Fig. 8. Example of topology created by hybrid buses. The transceiver acting as driver is coloured grey and the incident wave (not the reflexions) of the digital information is drawn with thick curly arrows. The active transceiver is driving more than one bus (AC terminated), and the local buses may be joined at other points than the extremes or the middle.

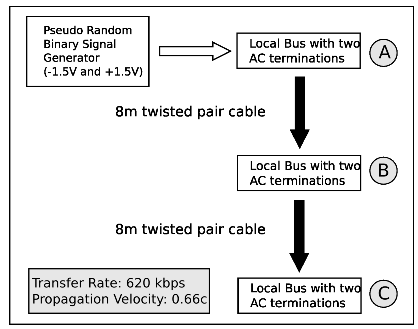


Fig. 9. Block Diagram of the Spice Simulation. The Pseudo Random Binary Signal Generator (PRBS) information is coupled directly to the first local bus (A); then it is forwarded to the second local bus (B), which is connected by 8 meters of cable; and finally, it is forwarded to the third local bus (C), which is connected by 16 meters of cable (8+8 meters).

only exceptions were the arbitrary behavioural voltage source used for the signal generator, and the transmission lines elements used to simulate the cables' behaviour. Fig. 9 shows the block diagram of the simulation.

The Pseudo Random Binary Signal Generator (PRBS) emulates the behaviour of a RS485 transceiver. Thus, the signals generated are $\pm 1.5V$ differential, which is the minimal output that several commercial transceivers can deliver; and the transfer rate for sending bits was set to 620Kbps, which is the maximum transfer rate estimated for Odin. Further, the rise and fall time of the digital signals are set around 35ns, which determines a realistic slope generated by fast transceivers; and the source impedance is 10Ω for both differential outputs.

The transmission line elements modeling the cables match the characteristic impedance (120Ω) and the propagation velocity ($0.66\,c$) of twisted pair cables. The characteristic impedance can be set directly in the Spice component, while the propagation velocity is implicitly set by the trip delay parameter, td, which is the time required for a signal to travel until the end of a line. Thus, considering a length of 8 meters per cable segment (see Fig. 9), td was set to 40ns (8/0.66c).

2) Results:

a) Reflexions: As expected, the use of non-ideal AC terminations in the local buses produces reflexions in the

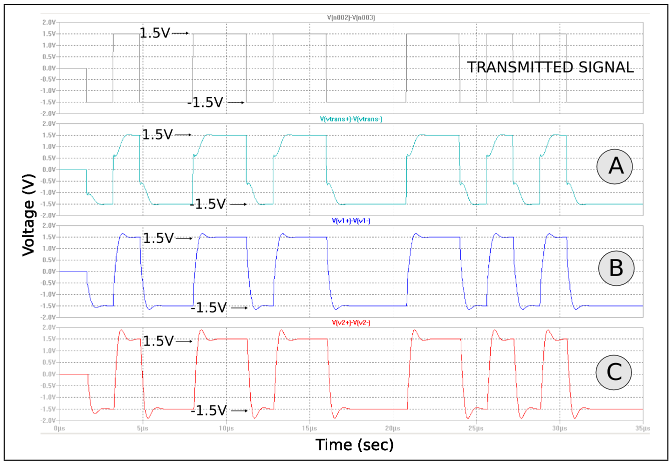


Fig. 10. Digital signal ideally transmitted, and then sampled at one extreme of each local bus: A, B, and C. The non-ideal AC termination produces reflexions, which are successfully damped before the pulses end. The maximum trip delay is the time required for a signal to travel 16 meters in twisted pair cable. In the hybrid approach, the bit width is 20 times the maximum trip delay, and the time constant $\tau = R_T C_T$, is 2 times the maximum trip delay.

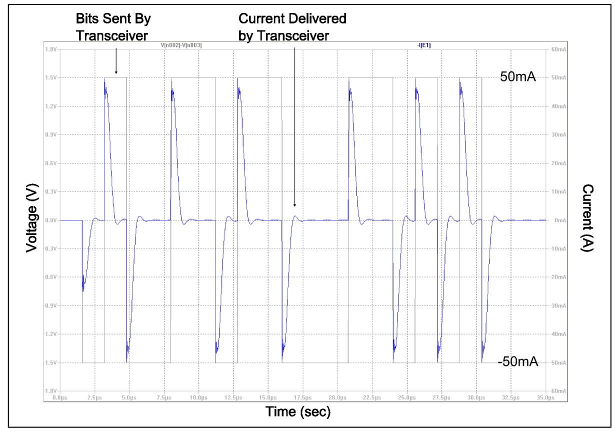


Fig. 11. Current being delivered or received by one of the differential outputs of the modeled transceiver. The current is positive and negative, but is always provided by the same same transceiver (from alternated differential outputs). The peaks achieved are within the capabilities of commercial transceivers.

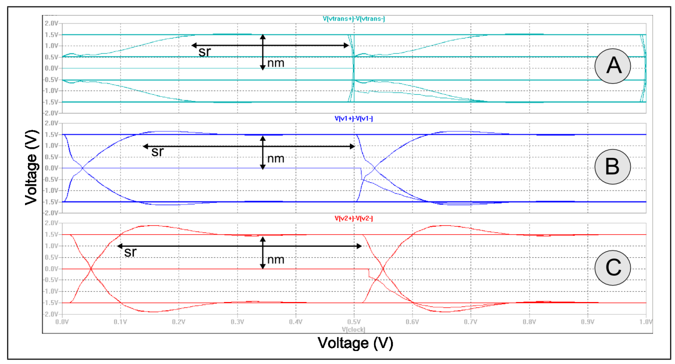


Fig. 12. Eye Pattern of the Spice simulation. The digital signals are sampled at one extreme of each local bus: A, B and C, but now against an appropriate synchronizing clock signal (not time in the horizontal axes). The bigger the distances nm and sr (or the more open the eye), the better the quality of the signal.

signals. Fig. 10 shows the same digital signal, at first ideally transmitted, and then sampled at one extreme of each local bus: A, B and C (see Fig. 9).

Thus, we see that all the reflexions are damped before the pulses end, which is a consequence of the guidelines followed for choosing the maximum transfer rate. With equation (8), we implicitly limit the *minimum* bit width to 20 times the maximum td (the time required to travel 16 meters).

Further, the time constant $\tau = R_T C_T$ is fast enough (2 times td) to produce overshoots and undershoots, more appreciable at the farthest end of the hybrid bus (C). The last is a typical pulse response of the AC terminations [18].

b) Current Requirements: To continue, the AC termination requires less current than the pure resistive termination, as shown in Fig. 11. There, we see that the peak values of the current are around $\pm 50mA$, which is within the range of possibilities of commercial RS485 transceivers.

Thus, from Fig. 11 we conclude that even if the voltage being transmitted is higher, meaning that the current required could be higher, the drop of voltage as consequence of overload would still be high enough not to produce transmission errors.

c) Reliability: An Eye Pattern gives us an evaluation of a digital system performance at a glance [19]. Thus, Fig. 12 shows the Eye Pattern obtained from the Spice simulation. There, we sampled the same signals as Fig. 10, at the points A, B and C, but now against an appropriate synchronizing clock signal (not time in the horizontal axis). The clock signal is a ramp of voltage with amplitude 1V and frequency equal to 620kHz divided by 2 (ramps per second). The last frequency allows to capture two eyes in the Eye Pattern.

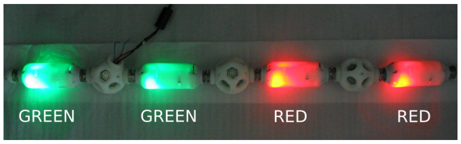
In Fig. 12, the distances nm indicate the amount of noise acceptable by the signals, before getting errors in the transmission (when the signals fall to $\pm 200mV$). These measurements decrease when increasing the length of the transmission line. On the other hand, the distances sr indicate the safety sampling interval, then not to fall into the slope segments where the signal can be wrongly interpreted. The intervals increase when increasing the length of the transmission lines.

We have to recall that in these measurements we excluded the resistance of the cables, which has an impact on the distances nm. Therefore, even if the results indicate us that the greater the length of the cables, the better the quality of the signal (smaller ratio nm to sr), an attenuating effect will be added when using non-ideal lines.

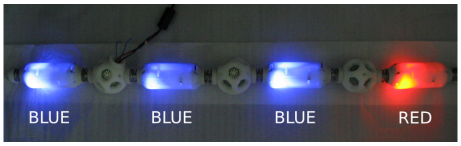
B. Proof-of-Concept

1) Settings: For the proof-of-concept we connected 4 Odin modules in a row, by using 3 joints that forward power and communication signals between modules. The modules are equipped with internal PWM-controlled RGB leds, which emulate the interface with future actuators of Odin. Fig. 13 shows the described arrangement.

Afterwards, we programmed the two middle modules to execute any of the following orders: light up with some colour,



(a) Two local buses: green and red.



(b) A hybrid bus: blue, and a local bus: red.

Fig. 13. Local and Hybrid communication between modules of Odin. Fig. (a) and (b) are the same system photographed at different instants of time. In Fig. (a) two pairs of modules are performing local communication: green and red buses. In Fig. (b) the three leftmost modules are performing hybrid communication: blue bus; and the rightmost two modules, still have local communication between them: red bus (not completely shown here).

stop lighting up, open switches, or close switches. On the other hand, the two extreme modules are programmed to send those orders to their neighbours, and to execute the orders at the same time.

The leftmost module orders to blink green, and the rightmost module orders to blink red (see Fig. 13a). Here the blinking (light up and stop lighting up) is executed in coordination with the modules sending the orders. Finally, the leftmost module has a peculiarity: after sending some blink green orders to its neighbour, it sends one close switches and several blink blue orders (see Fig. 13b).

2) Results: The result of the previous setting is that the modules begin by establishing two local buses: green and red buses in Fig. 13a. Afterwards, when the leftmost module decides, the green local bus is extended to become a hybrid bus: blue bus in Fig. 13b; allowing communication between the 3 leftmost modules instantaneously.

Here, we have to recall that all the buses can be coordinated independently. We made them blink at the same time, for the sake of descriptive information from pictures. When making the buses blink asynchronously, we could see in the second scenario (Fig. 13b) that: even when the hybrid bus is established (blue bus), the local communication between the last two modules is not lost (red bus).

VII. Discussion

Hybrid communication is specially useful when the system tasks can be split in roles [20] [21]. In that case, every role (e.g. leg, arm, or spine) can be coordinated by an specific bus, which has a highly optimized topology for the duty on hand. As the task or role changes, the communication topology can be once more optimized.

The main drawback of the hybrid communication approach is that, for small systems, communication between distant modules may not always be possible. A long hybrid bus connecting two extreme modules, could eventually divide the group into two blocks, therefore avoiding the creation of crossed hybrid buses. This problem may also appear in big systems presenting narrow passages.

In case the transfer rates provided by the hybrid communication approach are not enough for a specific system, the switching mechanism could be accompanied with bi-directional repeaters. Now, as the drivers load will be limited to one local bus, the local buses could be implemented with pure resistive terminations. Thus, the transfer rates may achieve the maximums estimated for the RS485 standard, which are 10Mbps or more considering the short distances covered by the local buses.

Nonetheless, even if the electrical isolation provided by repeaters will improve the response time of the overall system, the power required to drive every local bus will increase. Keeping the AC terminations will limit the transfer rates (higher than without repeaters) but will also keep the power saving features of the system. Thus, there is a trade-off between transfer rates and power saving.

Another way to increase the maximum transfer rates is to have a higher density of modules connected to the local buses. Odin is a good example of dense system, connecting up to 12 modules at once. Overall, these kinds of robots require less cable extension to communicate the upper limit of 256 modules.

To continue, a common aim of modular robotic systems is to reduce the size of the cells, and so the cable lengths needed for connecting higher number of modules. The last will translate into higher transfer rates when implementing hybrid communication.

Finally, as the communication technology evolves, we can see that transceivers decrease their load. Future improvements in chips will increase the maximum number of modules connected to the hybrid buses, making the hybrid communication approach a more scalable proposal.

VIII. Future Work

While reconfiguring the communication topology, the involved modules may not be allowed to perform coordinated tasks. Therefore, reconfiguration delay is an important parameter to have in mind when performing critical tasks, and is the future direction of our analyses.

Furthermore, the future work is also focused on testing the communication system in realistic applications, using Odin with higher number of modules involved, and where different kinds of communication topologies are required simultaneously.

IX. Conclusion

In this paper we presented a novel hybrid communication system for modular robots, based on inter-module buses, that can connect on-demand to form arbitrary network topologies.

By following the guidelines described in this paper, we can build systems with transfer rates up to 9.9Mbps divided by the maximum length of the hybrid buses measured in meters, with buses as large as 256 modules.

Overall, we think the hybrid communication approach is suitable for modular robots; improving transfer rates, flexibility, space requirements, power efficiency and reliability of the systems.

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