Wireless Communication and Power Transfer in Modular Robots

Maria del Pilar Olmos Cabrera, Ruslan S. Trifonov, Guillem Arimany Castells, and Kasper Stoy

***Abstract*— This paper presents two preliminary studies of the use of wireless technology for communication and power transfer for modular robots. Wireless technologies have the potential to be easily integrated into the complex mechatronics of a modular robot, but 1) wireless communication technology may have potential limitations in terms of localizing neighbor modules and 2) wireless power transfer may have too limited efficiency for practical use in modular robots. We demonstrate that by using a single omni-directional, printed-curcuit-board antenna it is physically possible to perform both local and global communication. For the purpose of localization we add a rotating, directional antenna to the system and demonstrate that in a controlled environment we can localize neighbor modules. In separate work, we find that wireless power transfer is not suitable for continuous powering of modules due to inefficiency, but suggest that it may find its use for charging of individual modules and connected configurations of modules. In conclusion, this preliminary work demonstrates some of the benefits and limitations of wireless technologies that can inform the future design of wireless modular robots.**

I. Wireless Communication

Communication is essential for sensing and coordinating movements in a distributed modular system. However, designing a communication system is complicated because it has to be robust to changes in the network topology and scale to a large number of modules. Typically, communication in modular robots is based on infrared or wired communication. The main problem of infrared and wired communication is that modules need to accurately align and orient to perform communication, which is especially problematic during connection and disconnection of modules. The environment also represents a problem for infrared and wired communication since dust and dirt can abrade or obstruct the infrared optics and, for wired communication, prevent electrical connections. These limitations have motivated the use of wireless communication technologies. Communication across connectors based on electrostatics has also been proposed [4], but suffers from similar limitations to those of infrared and wired communication. Bluetooth has received some attention [11], but suffers from scalability problems since it needs the presence of a central node coordinator. Radio Frequency (RF) radios, on the other hand, are free from the above problems, but has other drawbacks such as crosstalk and reduced ability to localize neighbor modules. The purpose of this paper is to document the advantages of RF communication and also to document the drawbacks of using RF for communication and localization.

The Maersk Mc-Kinney Moller Institute, Faculty of Engineering, University of Southern Denmark. The work is based on [2], [12], but Kasper Stoy is corresponding author [kaspers@mmmi.sdu.dk].

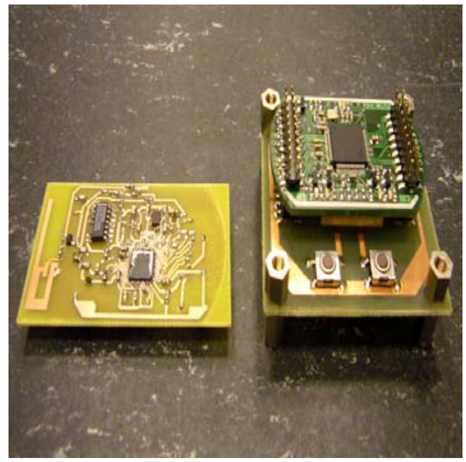

Fig. 1. Communication and General Boards

We design a *Communication Board* composed by a Texas Instruments CC2420 radio chip and a PCB antenna, implement a communication architecture, and use Received Signal Strength (RSS) technology to localize and solve the current challenges of inter-module communication and neighboring localization. We present both a single and multi-radio architectures and validate their performance through hardware experiments. Results show that wireless radios can provide low-cost, power-efficient and reliable global and local communication, but only limited neighbor localization for modular robots.

A. Hardware Design

The communication system is based on the powerful and at the same time low-power Atmel AT91SAM7256 32-bit microcontroller, which has 64 KB of RAM, 256 KB of flash programmable memory. The selection criteria for the radio device we considered were low power consumption, the possibility to use Received Signal Strength (RSS) methods and Direct Sequence Spread Spectrum (DSSS) technology, and being based on the IEEE 802.15.4 standard that operates at the unlicensed frequency of 2.4 GHz at 250 Kbps. Based on the above criteria, the TI CC2420 radio chip was selected and interfaced with the microcontroller through SPI links (the microprocessor and the communication electronics were on separate PCBs as illustrated in Figure 1). Although the device fulfills the ZigBee standard protocol, we designed and implemented a smaller protocol on top of the physical and MAC layers of the 802.15.4 standard, mainly because we did not need the extra functionalities ZigBee offers and because we could implement it according to our needs.

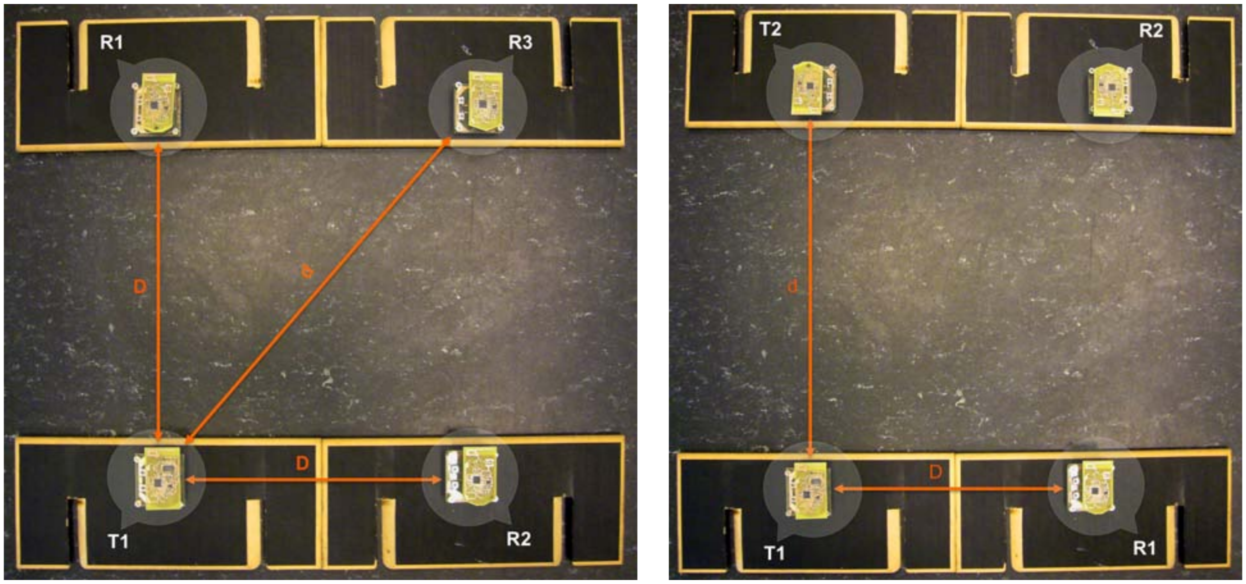

Fig. 2. Local and global communication test scheme modifying signal strength and channels.

We designed and implemented two prototypes: a single-radio prototype with an omnidirectional antenna and a multi-radio one with also a directional antenna. The omnidirectional design used is the PCB DN007 reference provided by Texas Instruments. The directional antenna is a circular open-waveguide low-cost implementation.

B. Software

The software used to embed on our modules is the lightweight TinyOS, designed to run on low-power wireless sensors with low storage capacity. We developed a new platform for TinyOS to port our hardware and implemented a Hardware Abstraction Architecture (HAA) based on the one that TinyOS already has to build the radio stack. The software and the communication protocol are implemented on the IEEE 802.15.4 stack to make a pair of modules communicate. Each radio used is set up either as a transmitter, a receiver or a sniffer using the same software. The sniffer was used for monitoring purposes. The main purpose of the software is to gather all the information needed for the experiments between transmitter and receiver modules.

C. Experiments and Results

1) Local and Global Communication: The architecture of the first experiment is based on a 2-D square lattice deployment of the modules using the first hardware prototype provided with an omnidirectional antenna. To provide reliable local and global communication without interference, we limited the distance between modules, modifying the signal strength and the communication channel. The separation between modules to avoid interferences is calculated with the Free-Space Path Loss (FSPL) equation that converts the CCRR (Co-Channel Rejection Ratio) from dB to Euclidean distance d to obtain the necessary separation between two radios for interference-free communication [5]. CCRR quantifies the necessary signal strength ratio needed between a desired and interfered signal. As we can see in Figure 2, D is the maximum distance where modules can communicate with its immediate neighbors when transmitting with specific output power. This distance is quite long for modular robots, mainly because the transceivers programmable output power is high. One solution to solve this problem is to choose another transceiver with better output power resolution, or use an attenuator to reduce the output power level. Furthermore, we demonstrated that with the architecture proposed the modules do not have problems of misalignment and orientation to communicate because of the performance of the omnidirectional antenna.

2) Neighbor Localization: In neighbor localization the goal is to estimate the positions of neighbor modules. In RF localization is still a big challenge due to the reflections and the omnidirectional antenna features. Kuo et al [6] propose a solution for localization based on 6 radios, one in each side of a cubic module. However, this solution has the disadvantage that it requires a significant amount of hardware, and as a consequence is more complex and expensive. Also, it has lost the ability to perform global communication. These facts, therefore, motivate us to find a cheap solution for local communication that does not loose the ability to communicate globally. To accomplish that we studied possible localization measurements and models used in localization algorithms. Our final experiments are based on the RSS method mainly because the other methods require more hardware to work. We tried to find the distance and orientation between modules to estimate the location of neighbors, however one PCB omnidirectional antenna does not provide us enough information to map out the topology. Therefore, we added a directional antenna to discover the neighbors by using the same receiver power strength indicator used on the last experiment (power output was 0dBm, max power consumption of the communication board alone was 52mW). But this time, and because the directional antenna only receives from narrow angle range, the module needs to rotate itself to discover which module wants to attach to it (acting like a RADAR as shown in Figure 3). The idea of rotation is based on this being imbedded in modules that are able to rotate (such as the ATRON modules [8]). An alternative would be to print four directional antennas on the PCB, but directional antennas with an operating frequency of 2.4GHz are relatively large and it is difficult to print directional antennas with small secondary lobes.

Our chosen solution can provide local and global communication with the aid of the incorporated omnidirectional antenna combining the scalability of local communication with the efficiency of global communication for small groups of modules. However, the solution does not provide the ability to detect multiple modules at the same time (only modules in the direction of the directional antenna are detected) and the secondary lobes of the directional antenna were high enough to interfere with the detection when modules were close to each other.

Fig. 4 shows that when transmitting at maximum power (0 dBm) the difference between the front and the backsides at 40 cm is only 9 dBm, but at 50 cm, the directivity of the antenna becomes ideal (the other modules are not receiving signal). However, one fact we should take into account with this configuration is that the orientation of the modules can differ. The orientation of the module with the PCB omnidirectional antenna produces a standard deviation of -7,21 dBm. The difference between the directional antenna pointing to a module or not is around 20 dBm, meaning that it is still possible to determine the neighbors position. The distance between modules is large, but improving the directional antenna will provide smaller secondary lobes and consequently reduce the needed distance. Also, we did not consider the effects of covering the antenna with metallic objects as is typically the case if they are to be embedded in a modular robot, so while the experiments are promising, they are somewhat inconclusive.

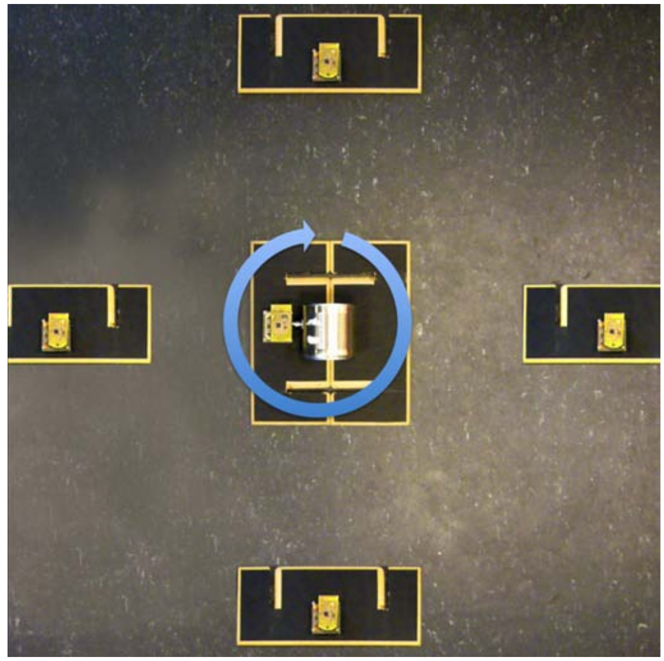

Fig. 3. Localization test scheme

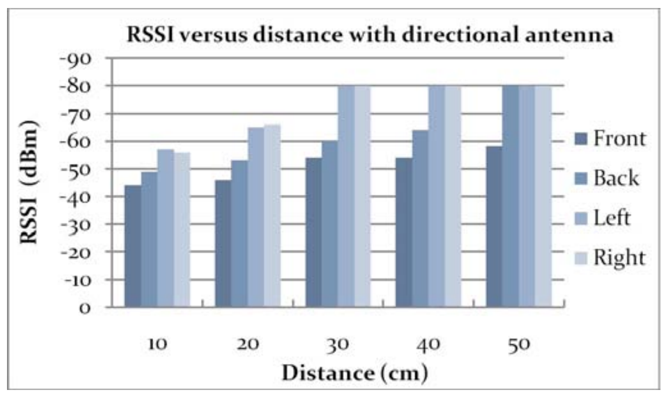

Fig. 4. RSSI values obtained at different distances and orientations with the central node looking at the North. A value of -80 dBm means that there is no communication between the transmitter and the receiver.

D. Discussion

We presented a new approach to achieve communication between modular robots through RF. We performed experiments to validate the suitability of RF for modular robots in local and global communication, and neighboring localization. The experiments successfully demonstrated the performance of the system without misalignment issues, and crosstalk problems. We also demonstrated a good approach to neighboring localization with the aim of the directivity of the antenna, though the distance between modules is long for the specific modular purpose. Selecting more suitable hardware (i.e. better radio chip device and improved directional antenna) can solve this problem. We propose the selection of another transceiver with more programmable output power levels, and to improve the directivity of the directional antenna by designing a circuit to change the operative frequency of the system to a higher frequency to reduce the size of the antenna and make it suitable for modular robots. At the same time, the use of the noisy 2.4 GHz band, which many other devices use, increases the interference from the environment.

II. Wireless Power Transfer

Powering a distributed, dynamic system such as a modular robot is a significant challenge and the solution chosen has consequences for the ease of experimentation, duration of experiments, and even the type of applications that can be considered. The most straight-forward solution is to equip each module with its own power supply in the form of batteries and charge individual modules as needed. This puts practical limitation on experimentation both in terms of module logistics and duration of experiments. A slightly more advanced solution [3], [10] is to add the ability of modules to share power and thus extend the potential duration of experiments since less active modules can donate their power to more active ones. It also opens up for single-tether charging or allow inactive modules to be taken out for charging without disrupting the robot. Applications that do not require the modular robot to move around may also benefit from being powered through the floor [7] and algorithmic work also demonstrates how this power can be distributed in the third dimension [1]. However, all these advanced approaches based on physical contact have several problems in common: they complicate connector design, expose electrical connections and through them vulnerable electronics, and make the electrical connections subject to dirt and wear and tear.

This background motivates our interest in understanding the potential and limitations of wireless power transfer for modular robots. In other applications such as biomedical implants the application of wireless power transfer has been proved possible [13], [9], hence those applications were used as the basis for application of the solution in the field of modular robotics. The solution proposed in this paper is resonance-based wireless power transfer between two coils. The technique aims for high quality factor which will provide higher efficiency in relative distance between modules. A proof-of-concept prototype has been implemented and tested. The efficiency was approximately 35% with resonance frequency at 247 KHz, the diameter of the coils ranged between 54 to 60 mm and the optimal operating distance was shown to be 5 mm.

The field of modular robotics has also the potential to benefit from this technology and to be used in specific applications, such as charging batteries of modules without dissembling a configuration or providing power to an unconnected, inactive module to make it possible for it to connect to a configuration. To be able to construct a resonant circuit which fulfills the specifications of the application, in which the model will be applied, is critical. To obtain those models, some complex mathematical models can be made and approximations to the real work achieved. With the help of a simulator or a mathematical program this can be performed efficiently. This paper will not present the mathematics behind the models but simply give outlines to what needs to be calculated and why. Complete mathematical models can be found in [12].

1) Inductance: The first step is to understand inductance. A simple wire is an inductor: as current flows though the wire magnetic flux is created, and a electromagnetic field is formed. The simple wire can be replaced by coil, which can be a wire around a solenoid core of ferrite material or even air. When the current is choked, a much stronger electromagnetic fields is created. This charging of the wire creates inductance. The current model uses an air core, despite lower efficiency than a ferrite core, for two reasons: 1) to reduce mechanical complexity and space requirements of embedding the model in modular robots, and 2) to understand if an air-core-based model is efficient enough to power modular robots.

2) Mutual Inductance: When two inductors' electromagnetic fields interact mutual inductance is created. Basically, mutual inductance is created when two or more coils are magnetically linked by common magnetic flux. Mutual inductance is a function of distance between coils. The further away they are placed from each other, the weaker the link. Alignment is also a significant contributor. Divination from the common axis of coils weakens the link. The magnetic coupling coefficient κ is based on mutual inductance and self-inductance.

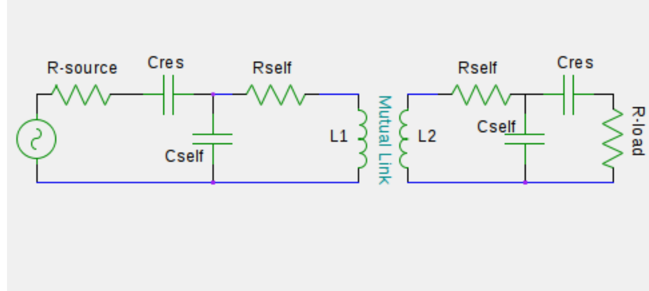

Fig. 5. Electrical circuit equivalent, $C_{res} = 4.9nF, R_{source}, R_{load} = 50\Omega$

3) Resistance: The resistance in the coil is important because in frequencies 4 times lower than the self-resonating frequency it helps to raise the quality factor. For higher frequencies it hinders the system and lower the quality factor. Resistance in a coil is the sum of three factors: DC resistance of conductor, AC resistance due to skin effect, and AC resistance due to proximity effect.

DC resistance is provided by the manufacturer of the conductor, and it depends on the diameter of the conductor and the operating temperature.

Skin effect is caused by concentration of current flowing near the surface of a conductor and not near the core of it. The effect is caused due to the magnetic flux in the center of the conductor being much stronger than those of the outer area of the conductor, forcing the density of the current flowing in the center to be less. The extra current is pushed to the outer area, and a bottle neck occurs. This leads to increase of the resistance.

A proximity effect is created when the magnetic fields of two conductors interact that increases the resistance of the carrier. If the current in two conductors flows in the same direction, the sides of the conductors which are closer to each other will be cut by more magnetic fields and forcing more of the current to flow through the opposite side of the conductor.

Both effects are related to the frequency of the AC current i.e. the higher the frequency the higher the resistance.

4) Parasitic Capacity: The charges flowing in wires next to each other in a coil creates parasitic capacity. The smaller the distance between turns the higher the capacity. High capacity cause the coil to self resonate at lower frequencies limiting the operating range between coils.

A. Coil Model

Figure 5 shows the electrical circuit equivalent of two coils. C_{res} is the resonating capacitor of 4.9nF tuning both

TABLE I

COIL MODEL CHARACTERISTICS

Coil	Inductance	Capacity	Resistance	Self Res. Freq.
Transmission	92μL	14pF	1.7Ω	1.34MHz
Receiving	90μL	12.5pF	1.6Ω	1.35MHz

TABLE II

PHYSICAL CHARACTERISTICS

Coil	Diameter	Length	Layers	Turns per layer
Transmission	60mm	2cm	2	20
Receiving	54mm	2cm	2	20

coils to resonate at 247KHz. R_{source} is the source resistance of a network analyzer and equal to 50Ω. C_{self} is the parasitic capacity which is parallel to the inductor. R_{self} represents self-resistance of the coil. The R_{load} is equal to 50Ω as the load of an ATRON module [8] is approximately 55Ω when powered up. Load resistance can vary depending on what operation the module is performing. The coils at resonance proved the highest value for current over the load resistance. Table I presents the working characteristics of the two coils.

B. Prototype

Fig. 6 shows the physical prototype of the model. Table II shows the characteristics of the prototype. Plastic was selected for core material, since it does not influence the magnetic field. The diameter of the coils has a small difference. By comparing Tables I and II, the effect of this difference is seen, leading to the conclusion that the size of both coils implemented in modules should be the same. It is possible, however, to have bigger coils for transmission than receiving in a charging scenario. A larger diameter of a transmission coil will increase the distance at which the coil is effective and can transmit.

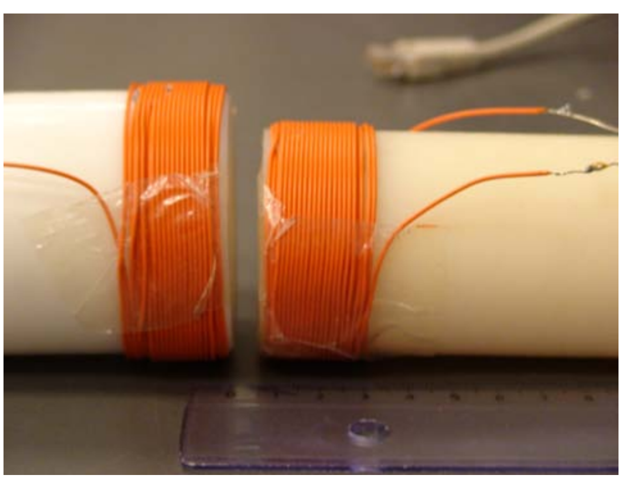

Fig. 6. Prototype of two coils with plastic core representing air

C. Experiments

In Fig. 7 the behavior of the model corresponding to the efficiency over the distance is shown. At $5mm$ the efficiency reaches almost 35% and then rapidly falls. This is caused due to the weak magnetic coupling. Less magnetic links connect the two coils at $10mm$ distance than $5mm$. In a model with more layers and tightly winded coils the magnetic coupling will be higher providing higher efficiency even at long distance. The efficiency is a function of the quality factor and the magnetic coupling coefficient. Quality factor by itself is a faction of the angular frequency, inductance and resistance. Higher inductance and mutual inductance with lower self-resistance can provide higher efficiency and a higher transfer rate.

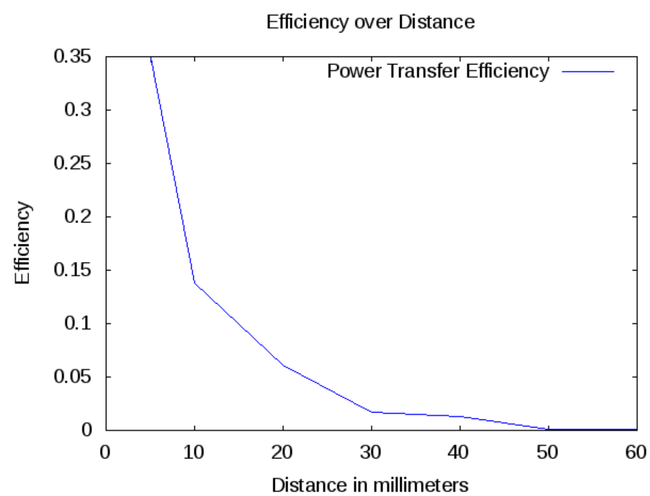

Fig. 7. Efficiency in percent as a function of the distance between two coils.

D. Discussion

Given the relative meager transfer efficiency of 35%, it is questionable to use wireless power transfer to distribute power in a modular robot. However, alternatively wireless power may be used for charging configurations of modules, without the need of dissembling them. Modules at the base of the structure can be charged; in return they can transmit the power via connectors to the rest of the structure. Another suggestion is that wireless power transfer can be used by modules to wake modules with depleted batteries to allow them to connect to a configuration and be transported to a charging point.

III. CONCLUSION

This paper documented our preliminary experiments with wireless communication and power transfer for use in modular robots. In terms of wireless communication we found that a single antenna system can be used for global communication and by controlling signal strength for local communication. However, the distance between modules in our succesful experiments is large due to limited resolution of control of the signal strength. We also demonstrated the potential of using a directional antenna for localization, but the practical usefulness of this approach is questionable. We continued to demonstrate simple power transfer between two coils of dimensions useful for modular robots and found that these provided insufficient efficiency for actual use in modular robots. Instead wireless power transfer might find use in charging of modules in and out of configurations.

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