An Experimental Study of a Bluetooth Communication System for Robot Motion Control

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***Abstract*—This paper presents a method that aims to reduce the complex cabling problem in robotics applications, so as to prevent difficulties in troubleshooting processes and failures in case of cable breaks. Examples in the literature have proven the reliability of the Bluetooth Low Energy (BLE) based communication systems and indicated that it could be employed in sensor data transfer applications. Therefore, our solution to the aforementioned issue is independent joint modules that comprise a motor driver, a microcontroller for running servo control loops, and a BLE device that enables the module to communicate with the main processor of the robot without the need of bulky cabling. Target applications for this method are mobile robots that encapsulate onboard processors and actuators that are deployed within a short range.**

***Index Terms*—Bluetooth Data Transmission, Bluetooth Low Energy, BLE, Antenna Alignment, Robot Motion Control, Mobile Robots**

I. Introduction

Robotic systems employ numerous sensors and actuators that require a power source as well as a connection to a central processing unit where the sensor data is processed and controller commands are sent into actuators. Hence, these systems accommodate complex cable trees that are prone to tensions and breaks, which might result in malfunctions in the robot's motion. Some of the widely used data transfer protocols in robotics applications are CAN bus, Ethernet, and EtherCAT [1], [2]. The common ground in these protocols is that all of them can be daisy-chained so that the number of cables in the system is reduced, however the risk of cable failures persists. To address this problem, we propose using Bluetooth Low Energy (BLE) for data transmission in robot motion control.

Bluetooth Low Energy, as the name implies, is a low power communication interface that operates in 2.4GHz (Scientific and Medical – ISM Band), transmitting data over 40 channels with 2MHz of channel width [3], [4]. The low power consumption of the BLE technology makes it a good fit especially for sensor applications [5]. Utilizing an adaptive frequency hopping technique (Frequency Hopping Spread Spectrum – FHSS), the robustness and the reliability of the connection is improved [3], [4]. Furthermore, the protocol supports up to 2Mbps data rate [3], whereas the CAN bus supports a data rate of 1Mbps [1].

Another alternative wireless solution to the problem could be Low Power WiFi (LpWiFi). LpWiFi supports higher data rates compared to BLE however the energy consumption of the LpWiFi is considerably higher than BLE [13]. Since the energy consumption is a major concern in mobile robot applications for longer operational times, the choice of wireless communication method was determined to be BLE.

The state-of-the-art robotic systems and medical devices make use of the BLE technology in many ways. Monitoring inertial measurement unit (IMU) data through BLE interface is one of the common implementations in the robotics area. Specifically, gait event detection in exoskeletons [6] and instrumented crutches for identifying forces acting on upper limbs [7] are some of the examples that implemented BLE for data transmission. In another application, BLE data transfer was utilized for test and verification of an inertial sensor situated on an industrial robotic arm [8]. In the medical area, researches have been focused on personal health monitoring via BLE. For personal ECG devices [9]–[11], blood sugar tracking devices [12] the BLE interface was utilized successfully. In [13], [14] stated that BLE can be used in sensor applications that demand high throughput.

Precise motion control in robotics applications is critical adressing the desired tasks without causing any harm to the outer environment. Utilizing state-of-the-art sensor technologies such as high-resolution encoders, more accurate motion control can be achieved. However, cable management becomes a crucial issue in robotic systems that comprise multiple actuators. Any break in the sensor cables would result the robot behave in an undesired way, which would be catastrophic.

To overcome this problem, we propose independent joint modules that utilize BLE in the data transfer between the actuators and the main processing unit of the robot. Thus, the number of required cables for the motion control per joint would be reduced to power cables solely. Proposed algorithms ensure that the robot completes its motion and stops smoothly in case of a connection failure in the BLE link. Beside the fail-safe algorithm, a custom-made directional gain antenna has been designed and attached to the joint modules, thus they

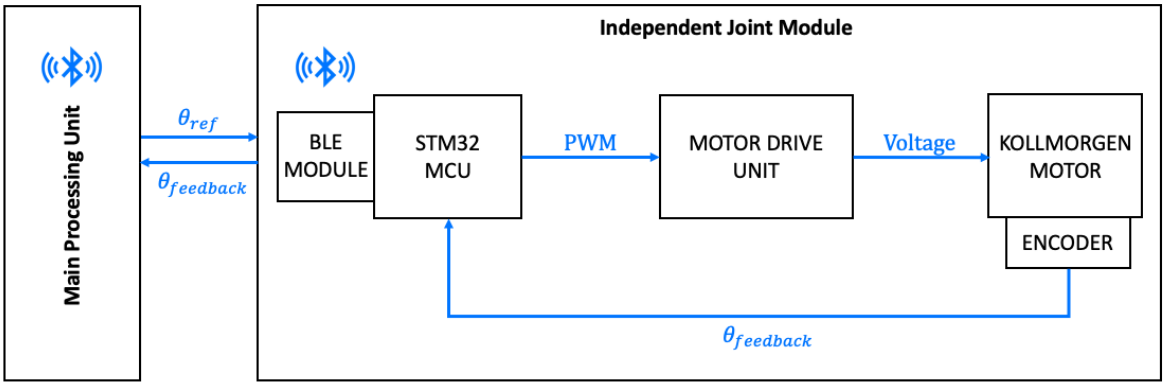


Fig. 1. Block diagram of the proposed independent joint module.

are aligned with the main processor's antenna. As a result, possible interference of signals in the same frequency may be prevented.

The rest of this paper is structured as follows: In Section II, the proposed method and its hardware blocks are explained. In Section III, test results for motion control through BLE is presented. Finally, in section IV, conclusion is given.

II. Proposed Method

The proposed independent joint modules are intended to be used in the motion control of robots. They comprise a microcontroller (MCU) where the servo control loops are handled, a power stage to drive the actuator, and a BLE module for communication with the main processor. The presence of the BLE has eliminated the requirement for long sensor cables, thus reducing the complexity of the cable trees in robotics systems.

To verify our method, we implemented a scenario where a single actuator of an exoskeleton is controlled wirelessly. In this application, a reference angle was transmitted from the main processor to the MCU and the encoder feedback is received by the main processor for monitoring purposes. With the proposed algorithm, it is guaranteed that in case of a connection failure, the actuator will continue its motion and stops smoothly when the initial position is reached, i.e. angle $\theta = 0$. At this stage, the independent joint module waits for the BLE connection to be restored, thus the user's safety is ensured. Moreover, we designed a special directional gain antenna that increases the immunity of the BLE connection to interfering signals available in the environment and thus we get a reliable wireless link.

In this application, two BLE modules are required and the one in the main processing unit side is configured as master, and the one in the independent joint module side is configured as slave. To enhance the security of the wireless connection, we utilized media access control (MAC) address filtering and password usage. When slave module is powered, it begins advertising for connection, however it connects only to the device with a specific MAC address, which is the master module. Upon the successful establishment of the connection, the slave module begins transmitting encoder data into the master and waits for the reference angle. For further enhancing the BLE's already existing reliable data transmission process [9], we applied cyclic redundancy check (CRC) algorithm to the data packets to be transmitted. Thus, we were able to avoid any erroneous data to be processed by both the independent joint module and the main processing unit.

A. *Hardware Architecture of Independent Joint Modules*

As illustrated in Fig. 1, an independent joint module incorporates various components that can be attached into a robotic system and provide mobility to the specific joints of it. In our application, the choice of microcontroller was a 32-bit 84MHz ARM Cortex-M4 core, 512KB Flash storage STM32F401 from STMicroelectronics [15]. The main objectives of the MCU are, reading the onboard encoder and running control algorithms for position control, handling the data transfer through BLE module and directing the received reference angle into the motor drive unit. The dedicated hardware block for floating-point operations makes this MCU well suited to precise motion control applications.

For the BLE interface, we utilized Texas Instruments CC2541 System on Chip (SoC), which is a cost-effective low power consuming solution [16]. It supports high data rates and communicate with the MCU through a Universal Synchronous/Asynchronous Transmitter/Receiver (USART) interface. Since the USART block provides double buffering and hardware flow control for RX and TX, it makes the chip suitable for high-throughput full-duplex applications [16]. The baud rate for data transmission between the BLE module and the MCU is chosen to be 115200 bps. The capability of the BLE module is supported with the designed directional gain antenna (see Section II-B).

The motor drive unit is Roboteq's SBL1360 Brushless DC (BLDC) motor controller that supports up to 30A of current rating [17]. The controller can decode Hall effect sensor signals, thus the commutation of the actuator is achieved. For the precise motion control, a 39-bit serial synchronous interface (SSI), energy harvesting absolute encoder from Broadcom is utilized [18]. With the energy-harvesting feature, the encoder

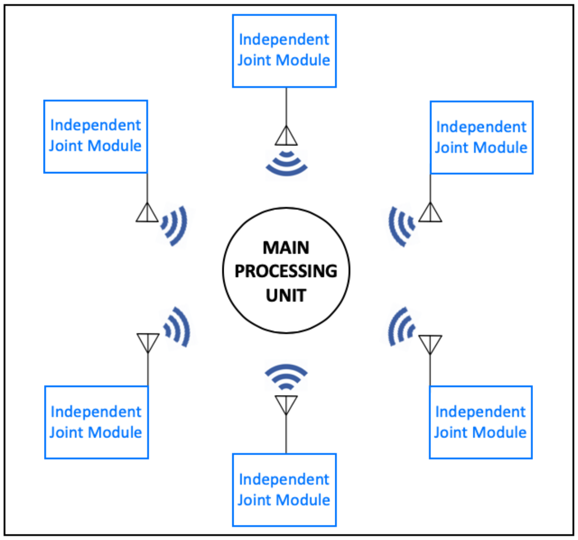


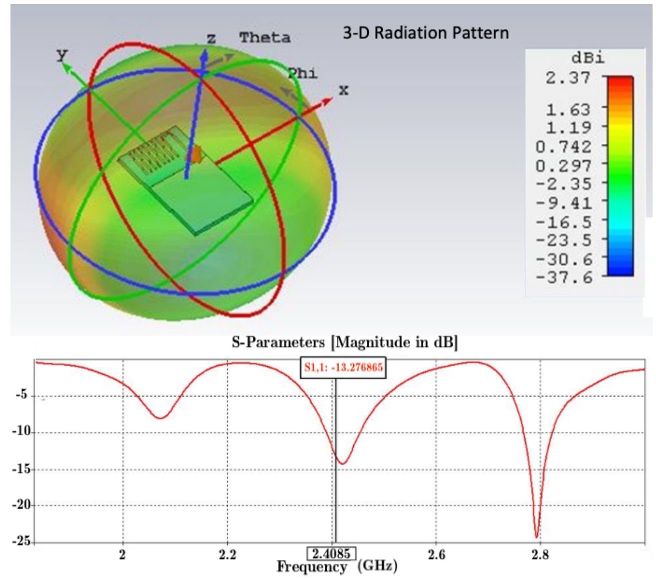
Fig. 2. A possible use case of independent joint modules with robotics applications that require multiple actuators.

provides the exact position of the rotating shaft even the external power supply is not available [18]. The encoder feedback is read by the MCU with serial peripheral interface (SPI) and translated into position data and thus it is used in the servo control loop. The final component in the independent joint module is a high torque three phase BLDC motor from Kollmorgen.

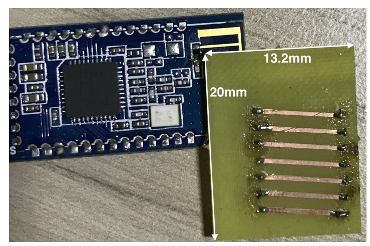
The proposed method is appropriate specifically for applications where multiple actuators are present, as in [19], [20]. There are similar standalone modules in the literature, however they use cable dependent data transfer interfaces such as EtherCAT and CAN bus [2], [20]. In Fig. 2 we illustrate the block diagram of a possible use case of such application.

B. Directional Gain Antenna

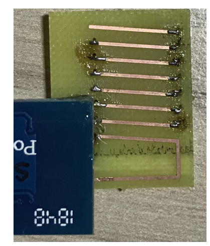
In an environment with multiple devices communicating in the same frequency may result in interferences and it might lead to failures. To reduce the risk of interferences, we designed a special 2.4GHz Bluetooth antenna with a high gain along the rotation axis that can provide a favorable signal-to-noise ratio to the main processing unit. It provides a natural filtering against the nearby interfering signals and hence enhances the immunity of the communication link. The total size of this two layer low-cost PCB spiral antenna is 13.2mm by 20mm. The antenna was prototyped on a 1mm thick FR4 substrate and soldered onto the carrier board of the CC2541 BLE chip, as shown in Fig. 3. The simulated 3-D radiation pattern of the antenna and the return loss without any external matching component are also shown in the same figure. The simulation results indicate that the return loss of the antenna was around 13dB at 2.4 GHz frequency. Further, the radiation pattern shows 2.37dB gain in the desired direction, which is verified with the measurements explained in Section III-B.



(a) 3-D radiation pattern of the antenna



(b) PCB top view



(c) PCB bottom view

Fig. 3. Planar spiral antenna with directional gain of 2.37dBi along the rotational axis of the joint.

C. Proposed Algorithm

Fault tolerance is one of the critical aspects in most of the robotics applications, specifically when there is a human-machine interaction. Any faults in the software would cause undesired reactions of the robot, which may cause harm to the outer environment. In this section we describe the measures taken in the algorithm in case of a connection failure in the BLE link between the independent joint modules and the main processor of the system.

Since we utilize a wireless data transfer system, the main concerns are possible connection losses and data corruptions. Since cyclic redundancy check (CRC) is one of the commonly used methods to detect data corruptions [21], in order to increase the reliability of the communication, we added a software CRC algorithm on top of the already available hardware CRC layer in the BLE stack [22]. For the data transmission between the main processor and the independent joint module we use a data frame as illustrated in Fig. 4. This way we can prevent possible corrupt data being processed by the microcontroller.

The flow chart given in Fig. 5 illustrates the working principle of the implemented software. Basically it works as follows, the independent joint module waits until the BLE connection

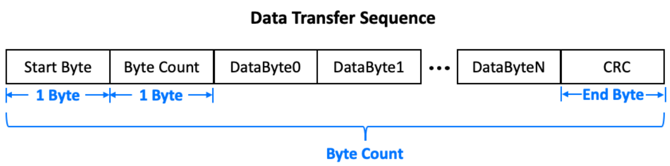


Fig. 4. A sample package used in the data transmission. Data bytes are mainly the encoder feedback sent from independent joint module to main processor and the reference angle sent from main processor to independent joint module.

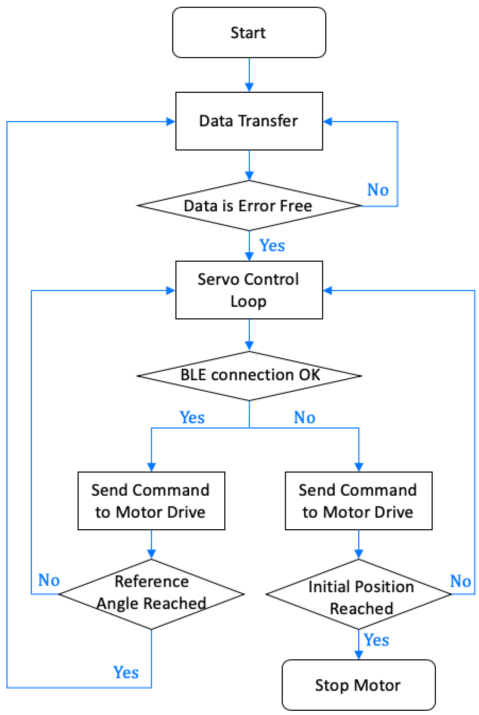


Fig. 5. Software flow chart for the independent joint module.

is successfully established. Then the main processing unit transmits the data, i.e. reference angle, to the independent joint module. The reference angle is sent with redundant bytes to handle the CRC check. When the data is received by the independent joint module, it is evaluated to interpret whether the packet is corrupted or not. If the packet is error free, the reference angle is passed to the servo control loop. Then, the MCU will send commands to the motor drive unit until the desired angle is reached. Meanwhile, the MCU checks the status of the BLE connection to understand whether there is a problem or not. In case of a disconnection in the BLE link, instead of immediately stopping the motor we let it reach to its initial position, i.e. $\theta = 0$ degrees, with an exponential decay function to stop it smoothly. Thus we can prevent any damages that might occur to the outer environment of the robot.

III. Experimental Results

In this section, we share the test results to our proposed independent joint modules. Firstly, in Section III-A, we introduce the results of the motion control tests under a disconnection in the BLE link, then in Section III-B, we illustrate the measurements related to the designed directional gain antenna.

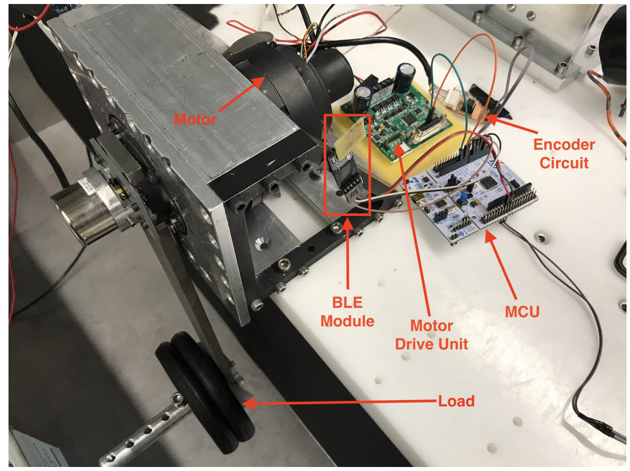


Fig. 6. Test setup of independent joint module.

A. Motion Control Tests

The main components of the independent joint module that are mentioned in Section II-A is given in Fig. 6. In this test, a Raspberry Pi 3 Model B is utilized as the main processing unit that transmits the reference angle values to the independent joint module and receiving the feedback data for plotting purposes only. The feedback from encoder is processed by the microcontroller of the independent joint module for the servo control loop that is run at 1kHz. Raspberry Pi 3 Model B is a single board computer with Quad Cortex A53 ARM cores operating at 1.2 GHz [23], running Raspbian OS with CONFIG_PREEMPT_RT patch enabled in the kernel for real time operation. The reasons of this choice were the price/performance ratio and the availability in the market.

In order to verify the proposed method, we focused on two different scenarios with two different reference inputs, i.e. step and sinusoidal. In scenario (1) the BLE connection is established and retained, in scenario (2), BLE connection is cut deliberately to observe the motor's behavior under the control of the proposed algorithm. In both of the scenarios, the duration of the tests were equal and set to be 20 seconds and a load of 5kg was attached to the motor to provide mechanical loading. First, a step reference value, i.e. $\theta_{ref} = 60$ degrees, was given to the independent joint module. In scenario (1) the motor reaches to desired angle and then remains in that position until end of the test, however in scenario (2), the BLE connection is cut in $t = 8$ seconds, where the algorithm kicks in immediately and sets the motor's angle into a predefined value, in this case to the initial position $\theta = 0$ with an exponential decay. Fig. 7 and Fig. 8 illustrate the resulting plots of the aforementioned scenarios. Secondly, a sinusoidal input is given to the independent joint module as reference. In scenario (1), the motor swings for 20 seconds and then stops, whereas in scenario (2), the BLE connection is deliberately cut at $t = 12$ seconds, then as in the previous test, the

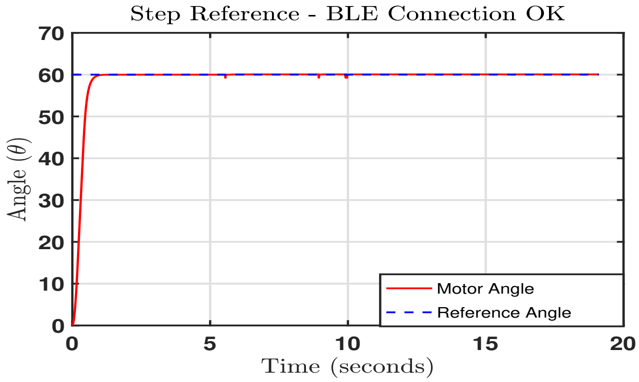


Fig. 7. BLE connection is maintained throughout the test

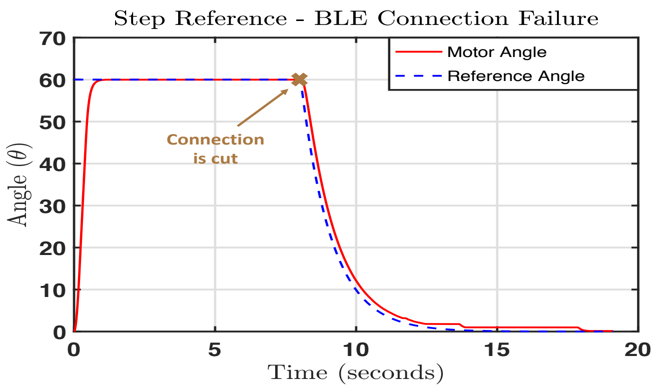


Fig. 8. Step reference - BLE connection is deliberately cut at $t = 8$ seconds

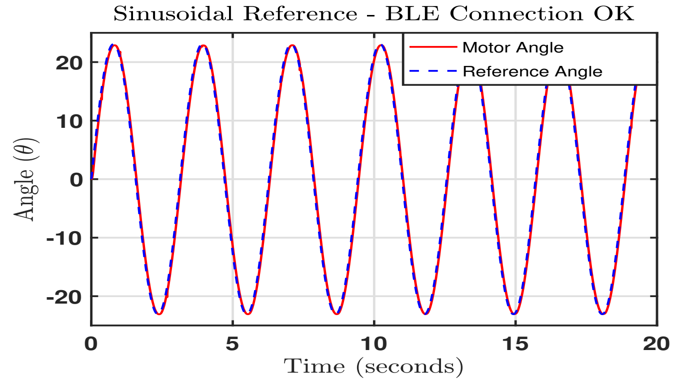


Fig. 9. BLE connection is maintained throughout the test

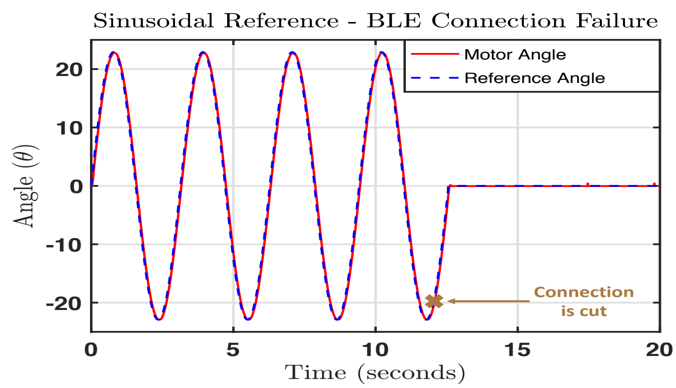


Fig. 10. BLE connection is deliberately cut at $t = 12$ seconds

algorithm handles the situation and instead of stopping the motor immediately, the motion is completed as it is planned until the initial angle, i.e. $\theta = 0$ degrees is reached. Resulting plots for the second test are given in Fig. 9 and Fig. 10.

B. Antenna Performance Tests

In this part, we explain the tests conducted to measure the performance of the designed planar spiral antenna. The measurements were completed via a mobile device with CySmart software, which is a debug and test tool for BLE [24]. Although the distance between the master BLE module and the slave will not be more than a meter in our intended application, we still measured the range capability of the designed antenna. During the tests, we observed that the connection between master and the slave is lost beyond 20 meters distance.

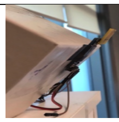
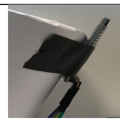
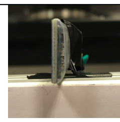
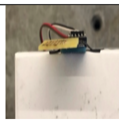
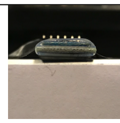
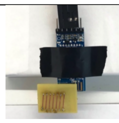
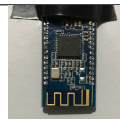
As mentioned in Section II-B, the designed antenna's performance varies according to its orientation. Since the joints of a robot will be in different orientations towards the main processing unit's BLE module (master), we had to decide the best orientation to install the slave module. To do that, we utilized the Received Signal Strength Indicator (RSSI) value of the BLE module. The measurements have been conducted within a range of a meter and a line-of-sight view was obtained with the master and the slave. Changing the orientation of the antenna resulted in various RSSI values, that are indicated in Table I. The performance comparison of the designed antenna and the antenna that was available on the carrier board of CC2541 chip is also given in the same table. From the measured values, we concluded that the best position to install the antennas on the robot is position 1, for the designed planar antenna (slave), and position 4, for the regular antenna (master). As a result, the BLE antennas in the independent joint modules (slaves) are positioned in the direction where the signal strength is the most, so that we get better immunity over possible interferences.

IV. Conclusion

As the number of actuators and sensors increasing in robotics applications, it is becoming harder and harder to interface these components with the processing units of the robots. Complex cable trees are required to establish data transfer links between processing units and sensors/actuators, however this might cause cable breaks in applications where the robot is not stationary. In order to prevent possible harmful results in such cases, we presented a method that propose a wireless solution for motion data transfer utilizing BLE. Since the proposed independent joint modules require only power cables, we were able to reduce the complexity and vulnerability of the cable trees in robotics applications.

Two test scenarios were implemented to evaluate the validity of the proposed method. Transmitting only the reference values into the independent joint modules, we were able to obtain the

TABLE I
ANTENNA PERFORMANCE MEASUREMENTS

Position	**Planar Antenna**	**RSSI Value**	**Regular Antenna**	**RSSI Value**
1		-64 dBm		-66 dBm
2		-69 dBm		-72 dBm
3		-74 dBm		-77 dBm
4		-78 dBm		-62 dBm

desired results without any problems. In case of connection failures, the motor completes its motion until it reaches to its initial position and stops smoothly. This way we could prevent possible harmful events to the outer environment of the robot controllers.

In a future work, we plan to encapsulate joint modules into singular units and integrate them with the exoskeleton joints designed in [25]. In addition, the proposed algorithm will be compared with the conventional ones in a future study. Although the communication delay was deemed to be insignificant in the assessment of the experimental results, further investigation will be conducted. For that purpose, various chips will be tested in terms of their throughput capabilities to choose the best option for our application. Lastly, we plan to improve the connection security applying encryption algorithms to the transmitted data in order to reduce the risk of interferences of the third parties.

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