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A Novel Connection Mechanism for Dynamically Reconfigurable Modular Robots

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Abstract: This paper describes a novel hermaphroditic, single sided disconnect physical connector for heterogeneous modular robots built using eight permanent magnets arranged in rotating pairs. The connector has 4 rotational degrees of symmetry and incorporates power and data sharing. The connector has been designed as part of a project creating 10 cm cubic heterogeneous modules but could be easily scaled to different sizes for other applications. The paper begins with an introduction to connection mechanisms in modular robots, followed by a detailed description of the design of the connector. A description of the simulation environment created to test systems of interconnected modular robots is given, followed by the implementation and testing of the connection system created.

1 INTRODUCTION

A modular robotic system consists of a set of interconnected robotic nodes, or modules, that together form a larger robotic system. There are various classifications of modular robotic systems, described in detail by (Brunete et al., 2017) and (Yim et al.,). The system described in this paper conforms to the categories of dynamically reconfigurable and heterogeneous. A dynamically reconfigurable system is one that can reconfigure it's structure during run-time to cope with local failures (such as ejecting a broken module from the system) or functionality changes (such as reconfiguring for different locomotion strategies or repositioning a sensor module for extended field of view). A heterogeneous modular robotic system is one in which the modules that make up the system are not all identical. These modules can interconnect to form a larger system through the use of a standardised mechanical and electrical interface.

Communication between modules was identified as a major barrier to better systems of modular robots. For modules to cooperate effectively, there is a need for both high throughput and low latency communication. The majority of modular robot systems to date have used Infrared, UART, CAN bus or Infrared diode pairs for their primary communication. While these work well for propagating control commands around a system, they do not work well for dynamically reconfigurable systems with both low latency and high throughput requirements. A network system providing higher bandwidth and more resilient communications for modular robots has been developed based on the IEEE 802.3 Ethernet standard for the physical layer. A novel networking protocol to handle data flow and topology discovery in the network is being developed for reconfigurable modular robotic systems. This research is focused around a system where modules have a 100mm cubic structure, constructed out of six submodular tiles. The submodular tile design enables the modules themselves to be modular and share common components in manufacture. This accelerates development of specialized heterogeneous modules and reduces design and manufacturing costs as well as facilitating investigations into hierarchical modularity. A dynamically reconfigurable modular system needs to be able to perform in-process physical reconfiguration. To facilitate this, modules must have a robust electro-mechanical connection mechanism that accommodates transfer of mechanical forces, power and communication data. The most fundamental design aspects of modular system design are the use of common communication and power transmission systems throughout these heterogeneous agents to allow them to create connect together for any configuration needed for a given task.

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These systems must be resilient to faults and failures as well as providing high communication bandwidth and power throughput to keep systems operating in harsh and challenging environments. Potential applications of dynamically reconfigurable heterogeneous modular robots include, but are not limited to: modular satellites; A modular satellite system would be greatly beneficial to the space industry because if there is a fault or upgrade needed, then a small, module payload can be sent to the asset, which will then autonomously reconfigure to accommodate it, rather than requiring a whole new asset al.together to fulfill requirements, reducing cost and extending in-service life of satellites.

The research contributions of this paper are; a novel interconnection and communications system for reconfigurable modular robots from the physical layer up that is designed to allow modules in a dynamically reconfigurable network to communicate effectively, a novel rotating permanent magnet-based physical connection mechanism for modular robots that allows single sided disconnect and reconnect, a system of sharing data and power using the permanent magnets as electrical conductors, and a heterogeneous, dynamically reconfigurable modular robotics platform that can demonstrate the effectiveness of these novel systems and how they enable further research to be carried out in the field of modular robotics.

2 Previous Works

This section provides a brief review of the literature to date regarding modular robotic systems. A review of the research history of modular robots is provided at first, followed by a quantitative review of communication systems used within modular robotic systems. Finally a review of power distribution amongst nodes in a modular robotic system is presented.

2.1 Modular Robots

Research into modular robotics systems was first conducted by Fukuda et al.(Fukuda and Nakagawa, 1988) in 1988 with the creation of CEBOT. Since then, more than 60 modular robot systems of varying capabilities have been developed for research purposes. Modular robotics have been identified as potentially beneficial to industries such as space(Yim et al., 2003), search and rescue(Pfotzer et al., 2014) and other harsh environments where a system that can dynamically reconfigure to cope with partial failures or contain built in redundancy mechanisms is desirable. There are a number of detailed review papers published regarding the field of modular robotics (Yim et al., ; Moubarak and Ben-Tzvi, 2012; Brunete et al., 2017; Ahmadzadeh et al., 2016; Feczko et al., 2015).

2.2 Communication in Modular Robots

Throughout the 30 year history of modular robotics research, authors have chosen to adopt many different communication standards for their platforms. As the underlying embedded technologies have evolved, so have the physical layers and protocols used. Figure 1 shows the usage of different communication standards across all the modular robotic systems reviewed over time. The modular robotic platforms are tabulated in Table 1. Thirteen individual protocols were found to be used. It can be seen that Infrared (IR) is the most widely used, with nearly a quarter of all modular robots using the technology. IR is a wireless protocol which is easy to implement in embedded systems, this is likely why it is the choice for many system designers. It is good for modular robotics as it does not require an electrical connection between modules, making mechanical design easier, but with the need for line-of-sight for communication to work and bandwidth limitations, it is unsuitable for a robust system. CAN is the second most popular choice for communications between modules. It was first used by Yim et al. in the CKBot Platform(Yim et al., 2007). CAN is a multi-drop bus based protocol which was originally developed for communication between processors in an automotive environment. Bluetooth has been popular too as it is easy to implement due to there being no need for electrical interface between modules and that there are many bluetooth-to-serial modules available commercially making electronics implementation easy. Problems quickly arise with bluetooth as the number of modules increase however, making it only suitable for small scale modular systems. Bluetooth was implemented in the YaMoR platform(Moeckel et al., 2006), with the authors noting that is was primarily chosen for ease of implementation. To date only one modular robotic platform has used Ethernet for communication between modules. This was CoSMO platform by Liedke et al.(Liedke et al., 2013). The authors cite the collision-free, high-speed, hot-pluggable properties of Ethernet influencing the decision to use it, along with the ability to have arbitrary topologies and accumulating bandwidth with the use of trunking of multiple packet routes simultaneously.

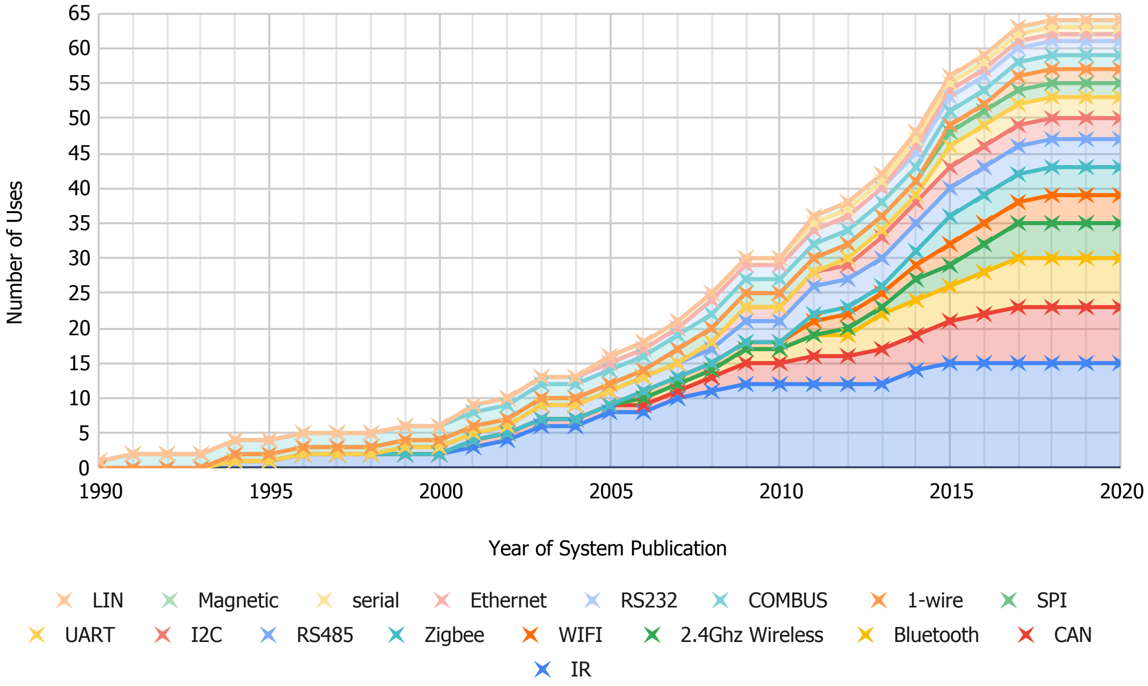

Figure 1: Chart showing the distribution of communications protocols used in modular robotics

3 Design

This section describes the design of the modular robotic platform created as part of this research.

3.1 Mechanical

Work has been ongoing to develop a mechanical connection system for the modular robotic system. The connection system must be hermaphroditic, where any module face can connect to any other module face. The connection mechanism must also allow the one module face to connect to another module face in any 90 degree rotation, so there must be four rotational degrees of symmetry. Finally the connection mechanism must allow for single sided disconnection, that is only one module needs to be able to initiate a disconnection. This allows for the system to eject a failed module. A review of modular robot connection mechanisms was carried out by Saab et al. in (Saab et al., 2019) which concluded that connection mechanisms with hooks or pins are vulnerable to abrupt impact forces, and claw-like mechanisms struggle to ensure rigidity. Magnetic connection mechanisms were identified as needing further investigation as there was little data on such mechanisms in macro scale modular robots.

Where a module is static, i.e. has no kinematic peripherals, and it has no sensors that require the use of a full face, all six sides of the module have an inter-module connection mechanism to allow power sharing and networking throughout the system. A full module is depicted in 2. Where a module has a face of it's cubic structure dedicated to a peripheral, that face may not have an inter-module connection mechanism. For example the castor module would not have an inter-module connection mechanism on the face that contains the castor wheel. The benefit of having a sub-modular tile design allows for application-specific tiles to be created and fitted to existing modules without having to design and build an entirely new module.

A magnetic based coupling mechanism has been developed to fulfil the requirements stated above. This system is based around eight magnets arranged in pairs that have a local frame of rotation. The connection face is shown in Figure 3. Each pair of magnets has one north pole at a normal to the connection face, and one south pole at a normal to the connection face. Each rotating magnet pair can rotate through 180 degrees. The mechanism is driven by a 298:1 gear ratio MP 6V Pololu Micro-Metal Gear Motor. A video demonstrating the rotating magnet pairs can be seen at (White, 2022b). The motor is mounted in the

Table 1: Modular Robotic platforms grouped by inter-module communication protocol

IR	(Yim, 1994) (Murata et al., 1994) (Rus and Vona, 2000) (Castano et al., 2002) (Suh et al., 2002) (Koseki et al., 2004) (Salemi et al., 2006) (Shimizu et al., 2006) (Jørgensen et al., 2004) (Gilpin et al., 2008) (Dorigo et al., 2013) (Salem, 2014)
CAN	(Yim et al., 2000) (Yim et al., 2007) (Yerpes et al., 2008) (Wei et al., 2010) (Baca et al., 2012) (Pfotzer et al., 2014) (Faiña et al., 2015) (Parrott, 2016)
Bluetooth	(Moeckel et al., 2006) (Wolfe et al., 2012) (Jia et al., 2015) (Yerpes et al., 2008) (Baca et al., 2012) (Parrott, 2016) (Ryland and Cheng, 2010)
2.4GHz Wireless	(Zhu et al., 2013) (Pacheco et al., 2015) (Faiña et al., 2015) (Oung and D'Andrea, 2011)
WiFi	(Dorigo, 2005) (Ryland and Cheng, 2010) (O'Hara et al., 2014) (Davey et al., 2012)
Zigbee	(Romanishin et al., 2013) (Zhang et al., 2014) (Baca et al., 2014) (Wei et al., 2010)
RS485	(Kotay et al., 1998) (Murata et al., 2002) (Lyder et al., 2008) (Lyder et al., 2010)
I2C	(Daidié et al., 2007) (Zhang et al., 2008) (Gambao et al., 2005)
UART	(Oung and D'Andrea, 2011) (Thakker et al., 2014) (Kee et al., 2014)
Others	(Neubert and Lipson, 2016) (Fukuda and Kawauchi, 1990) (Ünsal et al., 1999) (Zykov and Lipson, 2007) (Liedke et al., 2013) (White et al., 2004) (Gilpin et al., 2010)

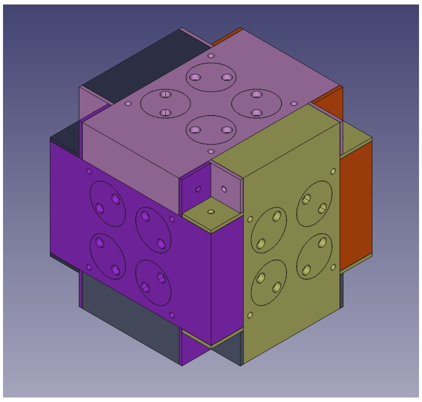

Figure 2: CAD render of full module composed of six sub-modular tiles.

center of the tile directly coupled to the driver gear in the connection mechanism. The gearing of the connection mechanism can be seen in Figure 4 The mounting for the motor can be seen in Figure 5.

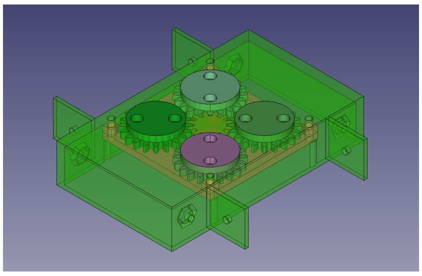

Figure 3: CAD render with translucent sub-modular tile depicting the connection mechanism.

The connection mechanism has three states of operation.

- Active Connect - In this state the magnet poles of the face are aligned with the opposing magnet poles of the opposite face. This creates a net attract force between modules and holds them together.
- Active Disconnect - In this state the magnet poles of the face are aligned with the same magnet poles of the opposite face, this creates a net repel force

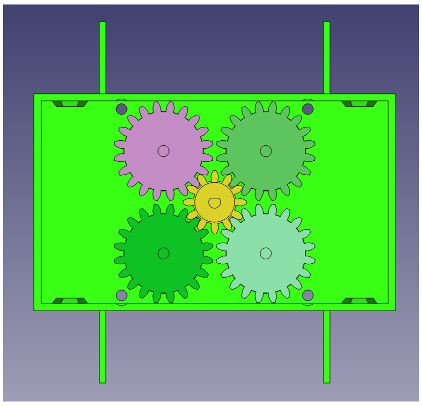

Figure 4: CAD render depicting the gearing of the connection mechanism.

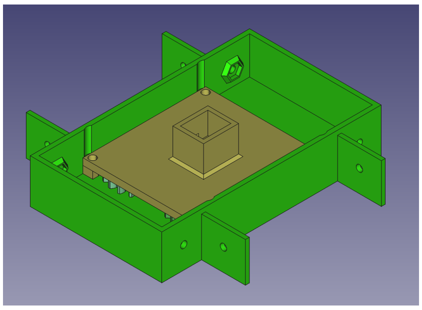

Figure 5: CAD render depicting the motor mount for the magnetic connector actuation.

between modules and pushes them apart.

- Passive - In this state the magnet poles of the face are 90 degrees offset from the magnet poles of the opposing face, this creates a net zero force between the modules.

The tiles are assembled into a full module using M3 bolts with corresponding nuts embedded into each tile. This allows for disassembly on a per-tile basis.

3.2 Electronics

This section describes the electronic design to realise a full module.

3.2.1 Electronics Architecture

The architecture of the electronics in a module is centered around a Xilinx Zynq 7020 SoC, which contains two arm processing cores and Artix-7 FPGA fabric. The FPGA portion of the device is utilised for all networking protocol implementation, connecting to 6 Ethernet physical layer transceivers, the TI DP83825. Each tranceiver then connects to the corresponding tile in the module, which contains the Ethernet transformer, and connection to the tile magnets. An overview of this architecture is shown in Figure 6.

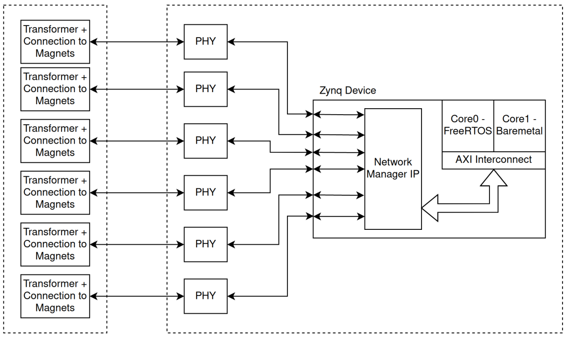

Figure 6: Block diagram depicting the architecture of the electronics in a module.

3.2.2 Networking

As identified above, there is a need for significant improvement in networking of systems of modular robots. A network supporting a modular robotic system must be resilient to a dynamically reconfiguring physical topology. It must also support both time critical control commands and high bandwidth sensor streams propagating through the system. The IEEE 802.3 100Base-TX Ethernet standard was used as a basis for the network hardware layer. 100Base-TX Ethernet uses two twisted pairs of copper conductors to operate full-duplex 100Mbps communication.

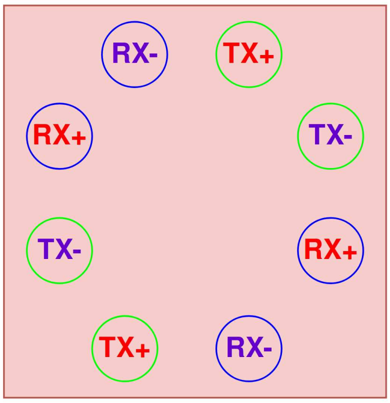

Figure 7: Configuration of Ethernet conductors on tile magnets.

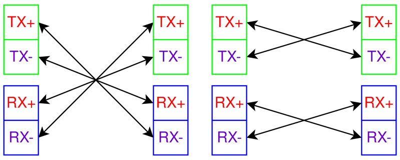

Figure 8: Ethernet connection permutations.

One major benefit identified for modular robots is that some Ethernet physical layer ICs have the ability to detect and correct for crossover of pairs and crossover of conductors in pairs. This means that, when the conductors are arranged correctly, two modules can connect in any orientation and the Ethernet PHY IC will identify the connection configuration operate as normal. The Ethernet data pairs are connected between modules using the magnets that mechanically hold the modules as conductors. Each conductor is connected to two seperate magnets, in the configuration shown in Figure 7. This configuration, where each conductor is routed through opposing sides of the magnet face, allows two tiles to connect in any orientation, and still maintain an active Ethernet channel. This configuration yields the connection permutations between two nodes shown in 8. These permutations are repeated at 180 degree rotation intervals.

3.2.3 Power Distribution

In using transformer-isolated Ethernet as the connection between modules, power can be distributed between modules using a modified version of the 802.3af power over Ethernet (PoE) standard. This is achieved by imposing a common mode voltage between the data pairs of the Ethernet channel via the center tap of the Ethernet transformer. This allows power and data to be shared between modules using the same conductors, reducing the need for more electrical contacts between modules which increases the complexity of the design. Work is ongoing to implement this into a module design, but initial tests have been done to verify the feasibility of transmitting power and data over an Ethernet channel with magnetic conductors with success.

4 Simulation

This section describes the simulation environment developed to aid development of of the software for this modular robotic platform. The simulation environment models both the mechanical properties of modules, and the communication channel used for module interconnection.

4.1 Simulation Overview

To enable development of networking protocols, reconfiguration algorithms, and task planning in this modular robotic system, a holistic simulation environment has been created to model the relevant aspects of the system. The simulation environment contains two main components. The physical simulation is performed using the Unity engine, and a custom POSIX compliant network simulator has been created to accurately model the network interconnections between modules. The network simulator is cyclically triggered from the Unity simulator. Arbitrary module configurations can be created in the simulator. Currently a model of a kinematically static module and a wheel module exists. With this, modular rovers can be created in simulation, like that shown in Figure 9

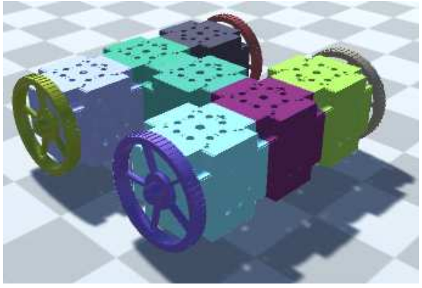

Figure 9: A modular rover configuration in simulation

Work is ongoing to perform experiments in simulation. Currently, some initial experiments have been run to test the models of the network side of the simulator. Experiments were run on a 3x3x3 module strictly orthogonal network of kinematically static modules. A broadcast packet is sent from one of the corner modules, and the time taken for that packet to reach all other modules in the system is recorded. This experiment is repeated with packet payload sizes from 1-5 bytes. The results from this experiment is shown in Figure 10. These results show the latency of the packet propagation increasing with payload size as expected. A render of the network of modules used in this simulation is shown in Figure 11. Once full integration of a module's mechanical and electronic components have been created, this experiment can be repeated in hardware to test the reality gap of the simulator, and tune the parameters of the models used.

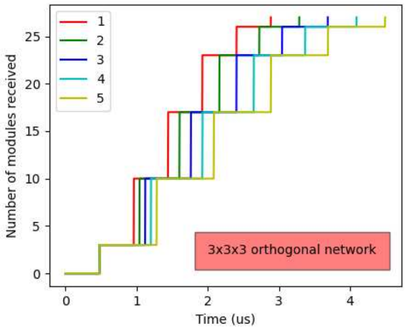

Figure 10: Simulation results of propagation delay of a broadcast packet in a strictly orthogonal network for varying packet payload sizes (bytes).

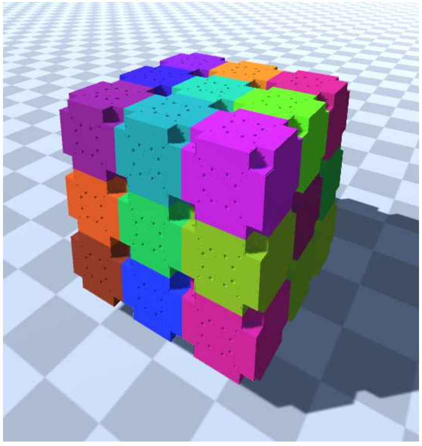

Figure 11: Render of a 3x3x3 strictly orthogonal network of modules in simulation.

4.2 Simulation Experimental Plan

Work is ongoing to perform more experiments in simulation. Now that hardware development is nearing completion, work can be done to implement topology discovery and routing protocols for the dynamically reconfigurable modular system. Once these implementations are completed, these can be tested in simulation to test their performance against other systems. The network model can be modified to accurately model other communications channels including SPI, CAN, UART, IR, etc. This will allow for quantitative performance comparison between the system implemented here and other communication systems used in other research projects.

5 Hardware Implementation

This section describes the current implementation of the module design described in the previous section.

5.1 Module Mechanical Implementation

The mechanical components of the modules have been 3D printed in PLA+. All printing was done on an Intamsys Funmat HT 3D printer. Images of an assembled tile and module can be seen in 12. The left module is in passive state, the right module is in active connect state. Tests have been carried out to verify that the connection mechanism works as described. A video showing the transition from active connect to disconnect can be seen at (White, 2022a).

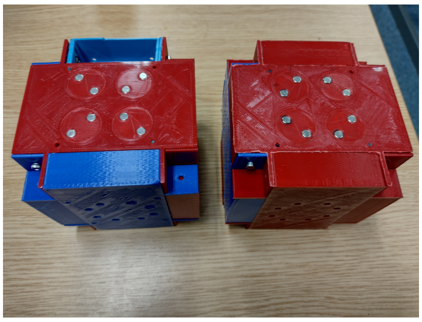

Figure 12: Left: assembled module in passive connection state. Right: assembled module in active connection state

5.2 Module Electronics

A PCB has been designed and manufactured, shown in Figure 13, around a Trenz electronic TE0720 System on Module (SoM). The SoM is a 4cm x 5cm PCB that contains a Zynq 7010 System on Chip (SoC), 1GB DDR3 RAM and 8Gb e.MMC non-volatile memory. It is designed to connect to a custom carrier board with board to board connectors for application specific uses. The carrier board designed for this project contains six TI DP83825 Ethernet PHY ICs, two CSI camera connectors, an SD card slot and connections for power, programming and GPIO access.

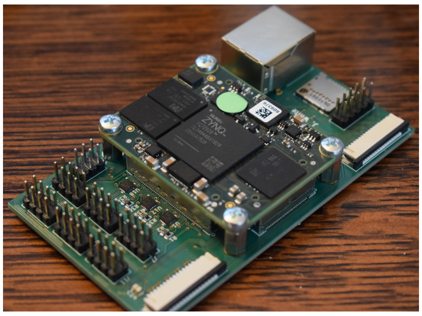

Figure 13: The compute module PCB populated with the TE0720 SoM.

6 Future Hardware Development Plans

Current hardware development has concluded the prototyping phase of the project. In the coming months a number of modules are to be developed and integration of system components completed to create a working modular robotics platform to demonstrate the work done here. To create a useful system, more than just kinematically static modules will have to be created, currently there are a number of heterogeneous modules scheduled for development.

6.1 Wheel Module

This module has a face with a motorised wheel attached to it. Each of the other five faces contain an inter-module connection mechanism. There is a networked microcontroller in the module with the appropriate motor control electronics along with the network processing FPGA.

6.2 Joint Module

A joint module contains 1 to 3 rotational degrees of freedom. These modules will allow the system to form kinematic chains for locomotion or manipulation of objects.

6.3 Sensor Module

A sensor module is a kinematically static module with a sensor attached to one or more faces. To date a camera module has been developed. There are plans to develop a module with rangefinders to aid in localisation and obstacle detection tasks. The benefit of having dedicated sensor modules is that they can be moved around the morphology of modules as required by the system for a given task.

7 Conclusion

This paper has presented the work done to date on a novel interconnection mechanism for dynamically reconfigurable modular robotics. The system described in this paper includes mechanical connection by way of rotating permanent magnets, communication using Ethernet for the physical layer utilizing the magnets as the electrical connection between modules, and power sharing via a modified power over Ethernet system using the same conductors as the data pairs. The system has been successfully protoyped and mechanically tested, work is ongoing to integrate the electronics and mechanical hardware together to perform holistic testing. Initial experiments have been performed in simulation to assess the accuracy of the network simulator. Work is ongoing to perform experiments with rover modules, and implement protocols for topology discovery and routing of data packets through the system.

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