HyMod: A 3-DOF Hybrid Mobile and Self-Reconfigurable Modular Robot and its Extensions

Christopher Parrott, Tony J. Dodd, and Roderich Groß

Abstract This paper presents HyMod, a hybrid self-reconfigurable modular robot, and its extensions. HyMod units feature three rotational degrees of freedom and four connectors, allowing them to move independently via differential wheels and group with other units to form arbitrary cubic lattice structures. The design is built around the high-speed genderless (HiGen) connection mechanism, allowing for single-sided disconnect and enabling units to rotate freely in place within their lattice positions. To our knowledge, HyMod is the first modular robot to combine efficient single module locomotion with free in place rotation. An analysis of HyMod is presented, as well as details of its mechanics and electronics. To augment the capabilities of HyMod, a number of extension modules are introduced. Hybrid modular robots with extensions, such as the system presented here, could see use in the areas of reconfigurable manufacturing, search and rescue, and space exploration.

1 Introduction

Modular robotics has seen numerous advances over the past decades, with the likes of M-TRAN III [1] and ATRON [2] successfully demonstrating the self-reconfiguration and collective motion of large chain and lattice structures. Each module within a modular robot is relatively simple, with typically only one or two degrees of freedom (DOF), allowing many modules to be produced at relatively low cost. Unfortunately, this means that such modules have limited or no mobility outside of a configuration. Efforts have been made to address this, with swarm systems gaining the ability to self-assemble [3], and modular systems gaining dedicated drive mechanisms to provide efficient single module locomotion [4, 5]. These sys-

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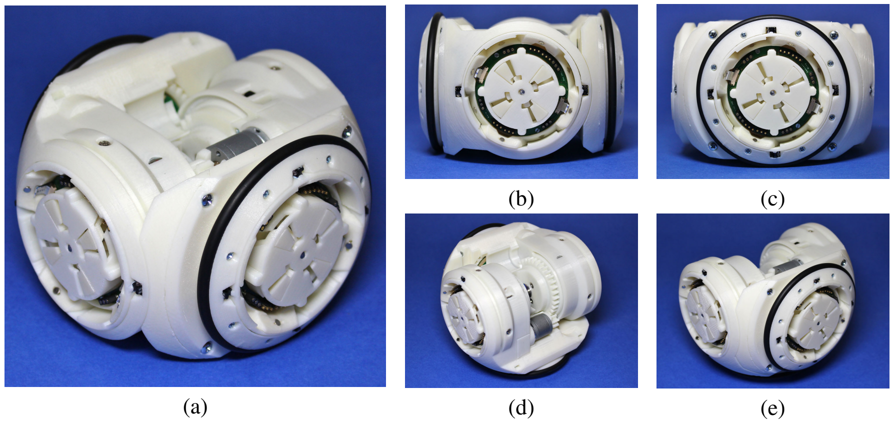


Fig. 1 HyMod: a new self-reconfigurable modular robot with three degrees of freedom (two of which form differential wheels), and four genderless connectors with single-sided disconnect. The module is shown from an (a) isometric, (b) front, and (c) side view, with its central rotational joint at zero degrees. The central joint is also shown at (d) -90, and (e) +90 degrees.

tems demonstrate the advantages of mobile modular robots, but compromise module self-reconfigurability in favor of individual autonomy. So far, only one modular system, to our knowledge, features efficient module mobility without sacrificing on self-reconfigurability [13, 14]; however, it lacks important features from the field such as inter-module communication and power sharing. This highlights the need for further modular robots that retain the features and reconfigurability of past successful systems, whilst also offering efficient single module locomotion.

This paper presents HyMod (Figure 1), a self-reconfigurable modular robot that is a hybrid between chain, lattice, and mobile reconfigurable robots [6]. It extends upon preliminary work presented in [7]. Inspired by systems such as PolyBot [8] and CKbot [9], HyMod features a central rotational DOF capable of moving ± 90 degrees, and is designed to form arbitrary cubic lattice structures. Two further rotational DOFs are mounted perpendicular to the central rotational joint, serving the dual purpose of emulating a spherical joint and enabling the module to drive around using a differential wheel setup. The arrangement of rotational axes shares similarities with the RobMAT [10] platform, and the use of reconfiguration joints as wheels has been explored on the iMobot [11], M^3 [12], and SMORES [13] platforms. This implementation removes the need for a separate drive mechanism for locomotion, as is the case with the modules of the Symbrion / Replicator project [15].

Connections to neighboring modules are achieved using four high-speed genderless (HiGen) connection mechanisms [16], one in each wheel and two along HyMod's central rotational axis. The connectors operate by extending hooks out of their housings to latch on to the hooks of an opposing connector, making a connection. The use of HiGen connectors gives HyMod several advantages over other connection mechanisms, most notably the ability to independently disconnect from and produce clearance between neighboring modules. The choice of connector gave

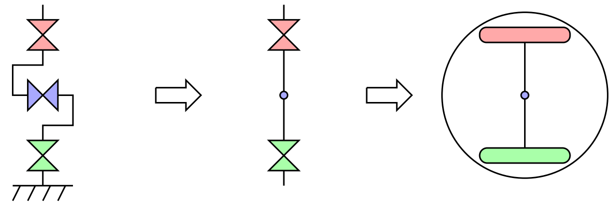


Fig. 2 The transition from the side view of a 3-DOF spherical joint (left) to a top view of a differential wheel setup (right), via an intermediate step where the middle DOF is locked at 0 degrees.

rise to the HyMod's spherical design, which allows all three of its degrees of freedom to actuate simultaneously without colliding with neighboring modules.

The remainder of this paper describes the design and implementation of HyMod (Section 2), and presents experiments conducted with a single unit (Section 3). A number of extension modules for HyMod are then explored (Section 4). Finally, Section 5 concludes the paper and discusses future work.

2 The HyMod Unit

The goal of HyMod was to create a module to address the division between mobile and self-reconfigurable systems, by integrating an efficient locomotion method that could also have a use on modules within chain or lattice structures (e.g. as a degree of freedom in a kinematic manipulator). Although the modules of systems such as M-TRAN can move independently, they are slow and have limited control over their heading when moving. A more efficient method of locomotion is that of wheels, as these can provide a constant velocity to a robot and allow for controlled turning.

To incorporate wheels into HyMod, the concept of a spherical joint was adopted (Figure 2, left). Typically modules designed to reside in a cubic lattice have a central rotational DOF that goes from -90 to +90 degrees, allowing for a free end to move between three faces of a cube, relative to a fixed end. By adding a rotational DOF to the fixed end, the free end is able to move between five faces. Additionally, by applying a rotational DOF to the free end, any item attached to it can be oriented arbitrarily. If the central rotation axis of this spherical joint is set to zero degrees (Figure 2, center), the remaining axes become in-line. By placing wheels on these axes a differential wheel setup is created (Figure 2, right), granting HyMod locomotion capabilities on par with various mobile swarm robotic systems available.

2.1 Geometry Analysis

From examining the 3-DOF spherical joint (Figure 2, left), it is apparent that an element of symmetry exists, as swapping which end is fixed can result in the same

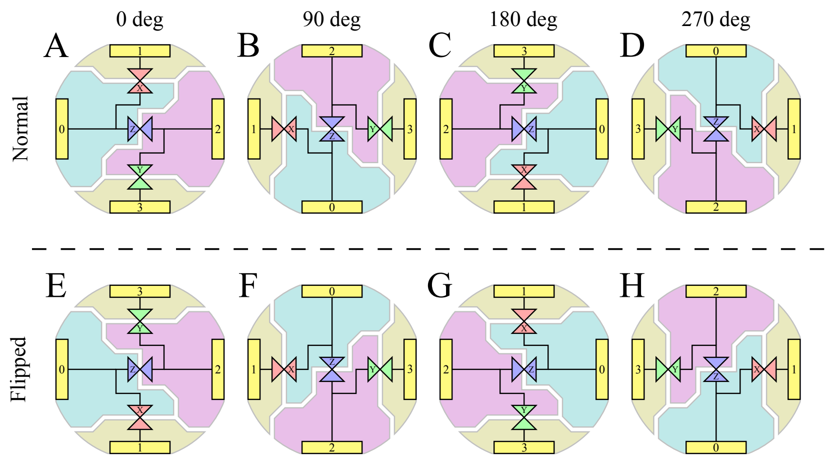


Fig. 3 The eight ways a HyMod unit can be oriented, as viewed on a 2D plane. Connectors are depicted using yellow rectangles, and are labelled 0 to 3. Rotational DOFs are depicted using connected triangles and are labelled X to Z. In this arrangement, connectors 1 and 3 can be rotated continuously, whereas connectors 0 and 2 can only be rotated ± 90 degrees.

Table 1 The connector and joint index changes when mapping one HyMod orientation to another.

Map				Connectors				Joints		
A	B	E	F	0	1	2	3	X	Y	Z
↕	↕	↕	↕	↕	↕	↕	↕	↕	↕	↕
C	D	G	H	2	3	0	1	Y	X	Z

movements, provided appropriate control remapping occurs. By discovering what these symmetries are, the isomorphic configurations that can be created with a given number of HyMod units can be determined, thereby reducing the search space complexity of any self-reconfiguration algorithm that may be employed on the system.

Figure 3 shows the eight possible orientations of a HyMod unit. The orientations are depicted on a 2D plane with the central rotational joint set to zero degrees. This can either be thought of as a top-down view of the modules resting on their wheels, or a side view with the modules anchored to a surface via their bottom connectors. The module has a rotational symmetry of two, meaning that of the eight orientations shown, only four are unique. The connector and joint mapping to go between one orientation and its symmetric version are shown in Table 1. As an example, to map orientation A to C, commands that would be sent to connectors 0, 1, 2 and 3, would instead need to be send to connectors 2, 3, 0 and 1. Similarly, commands to joints X and Y would instead be sent to joints Y and X, with Z remaining unchanged.

Using the knowledge of module symmetry and the four times symmetry of HiGen connectors, the number of isomorphic configurations of two modules can be determined. By applying the mapping and discarding configurations where a con-

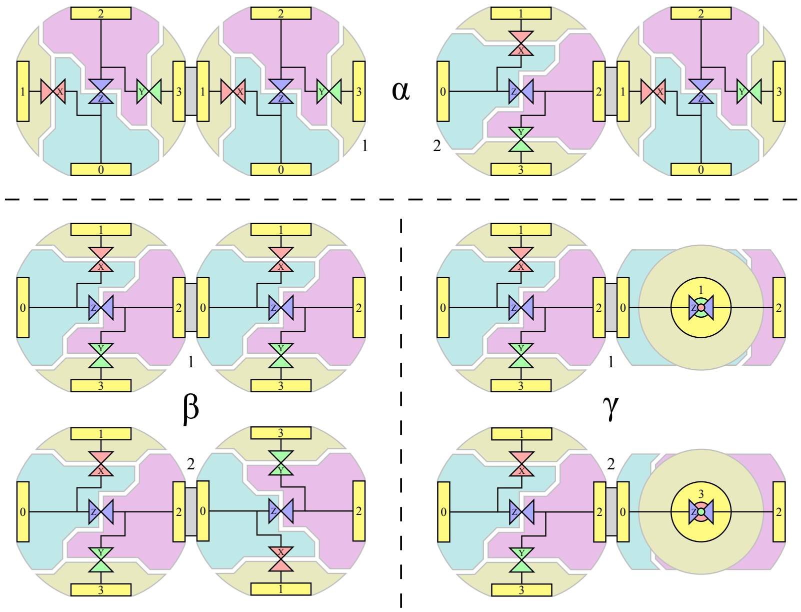
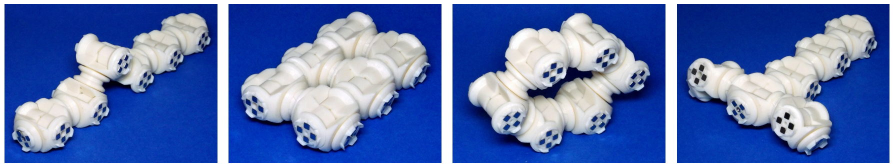


Fig. 4 All six of the isomorphic configurations that exist for two connected HyMod units.

nector symmetry offset (e.g. 90°) is equivalent to a wheel rotation, six isomorphic configurations are produced. These can be seen in Figure 4. Of the six, the two configurations labelled α offer a higher number of quantized joint angle combinations, 36 (3 x 4 x 3) versus the 9 (3 x 3) of the four other configurations. This is because those two configurations contain at least one continuous rotational degree of freedom between the two modules, featuring four quantized angles versus the three of the central joint. Note that rotations of wheels not connected to another module were discounted here, as they can be cancelled out by connector symmetry. Similarly, when two wheels are connected together their rotational degrees of freedom are in-line and can therefore be considered as a single joint.

As the design of HyMod is based on a spherical joint, it only occupies a single cubic lattice position. This means that in order to self-reconfigure, either four modules are needed so that a loop can be formed, or two modules and some kind of support surface (either a custom made structure or a grid of modules). By using a support surface, and provided both modules are adjacent to it, all of the isomorphic configurations of two modules (Figure 4) can transform in to each other without moving between lattice positions [1]. If only one module is adjacent however, and the configuration is one of the four labelled β or γ, self-reconfiguration is not possible

[1] Note, if a surface is made up of passive HiGen connectors, that being connectors without the ability to retract their hooks, then it is not possible to self-reconfigure in to, out of, or between the two configurations labelled γ even if they are adjacent to the surface, as clearance cannot be created between the surface and the modules to allow for such a rotation.



(a) (b) (c) (d)

Fig. 5 Examples of four possible HyMod robot configurations, using scale models: (a) snake, (b) 6-wheeled vehicle, (c) rolling track, (d) crawler.

as there are no perpendicular rotational axes available to move the other module to be adjacent to the surface. This suggests that one or both of the α configurations should be considered the metamodules [17] of the HyMod system. By using these metamodules, arbitrary connected 3D structures can be formed. For example, a cube structure can be built using $n^3/2$ metamodules, opening up the possibility for configurations of HyMod unit to be formed via self-disassembly, whereby modules in the cube can either become part of the final configuration or act as a temporary scaffold to support the disassembly process. A render of a cube formed out of 32 HyMod unit metamodules can be seen in the online supplementary material [26].

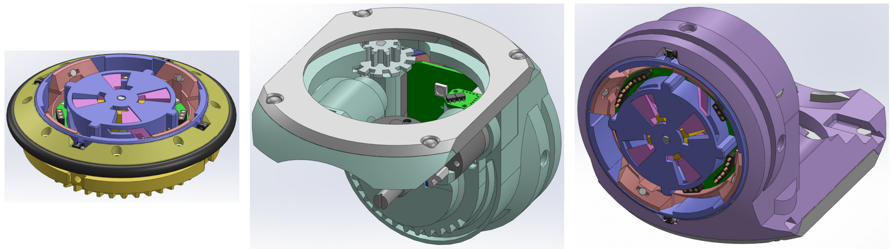
2.1.1 Example Configurations

To explore the possibilities of the HyMod unit's design before production, six scale models were produced. They consist of four 3D printed components each and four perpendicularly mounted permanent magnets per face. This arrangement of magnets emulates the genderless property of the HiGen connector. Examples of common modular robot configurations using the scale modules are shown in Figure 5.

2.2 Hardware Details

The module is built from two mirrored halves, forming a rotational hinge joint. This arrangement of identical halves is common with several modular robots, such as ATRON [2], Molecubes [18], UBot [19], and CoSMO [5]. Each half consists of a chassis housing two HiGen connectors; one in parallel to, and the other perpendicular to the hinge axis. The parallel connector is fixed to the chassis whereas the perpendicular connector has a rotational degree of freedom through its center, forming a wheel. This gives a total of four connectors and two wheels per module.

HiGen connectors (described in more detail in [16]) operate by using a central drive motor to translate and rotate four hooks. These hooks latch on to hooks of an opposing connector, creating a genderless connection that allows for single-sided disconnect. As part of this latching process, electrical connections are made, allowing for communication and power transfer across the connectors.



(a) (b) (c)

Fig. 6 3D renders of the HyMod unit's (a) wheel, (b) processing half, and (c) power half.

Each HyMod unit consists of sixteen custom ABS plastic components (excluding the four connectors) created using 3D printing technology, fifteen custom circuit boards, two slip rings, two battery packs, and several off-the-shelf items. Four DC geared motors are used to drive the three degrees of freedom of the module (two paired together for the hinge joint), each with a ratio of 154:1 and a quoted torque of 847 mNm at 6 V. An additional 5:1 gear ratio is applied on top of each motor gearbox, increasing the torque of the rotational joints and allowing the motors to be offset from each drive axis. This setup is what facilitates the use of two motors to drive the hinge joint, enabling all motors to be identical whilst allowing the hinge joint to offer effectively twice the torque of the other degrees of freedom. This also simplifies their control because the same driver electronics can be used for each motor. The housings of the four connectors are modified from the original design to allow for extra mounting points for the wheel hubs and the addition of infrared sensors for distance sensing. Internal sensing is achieved using a potentiometer, two optical encoder setups, and an Inertial Measurement Unit (IMU). To allow for continuous rotation of the wheels whilst passing power and communication to their connectors, slip ring components are used. This is a solution adopted by past systems [2, 20].

The module measures 128 mm x 128 mm x 94 mm, when the hinge is at zero degrees. The size is governed by the dimensions of the HiGen connector, the height of the slip rings, and the chosen wheel diameter of 94 mm. This wheel diameter gives the module a 4 mm ground clearance when oriented for driving. The separation between modules in a cubic lattice is 140 mm due to the connectors extending out of their housings by 12 mm during connection. To take advantage of this ability the module is designed to fit within a spherical volume, allowing for rotation around three axes without risk of colliding with neighboring lattice modules [16, see Figure 4]. As such the module shares visual similarity with the Roombots [20] platform, which uses its spherical design to enable the wheel-based locomotion of modules, rather than to provide clearance for self-reconfiguration. Figure 6 shows renders of the three main sections that form a complete HyMod unit. Additionally, a breakdown of the main HyMod unit properties is shown in Table 2.

Table 2 Properties of a HyMod unit

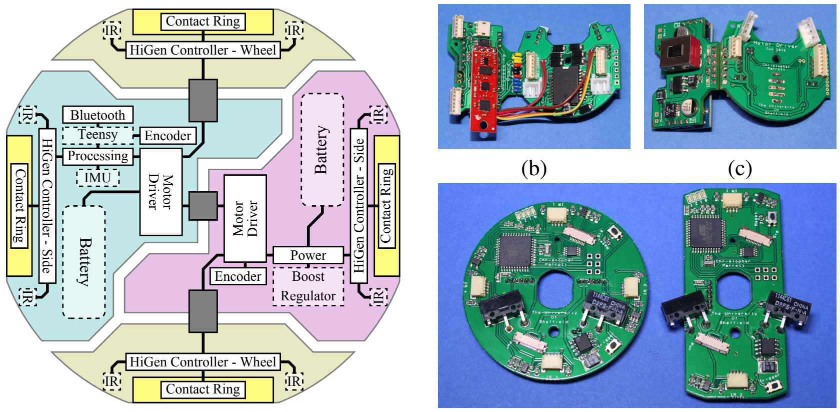
Property	Value
Size	128 x 128 x 94 mm
Lattice spacing	140 mm
Ground clearance	4 mm
Weight	810 g
Controllers	1x *PJRC* Teensy 3.2
	4x *Atmel* ATmega324P (*HiGen controller*)
Communication	1x EGBT-046S Bluetooth modem
	1x *NXP* fault-tolerant CAN transceiver
Sensors	1x *Sparkfun* 9 DOF sensor stick IMU (accelerometer, gyro, magnetometer)
	12x *Vishay* reflective optical sensor (infrared proximity)
Motors	4x *Pololu* 154:1 metal gearmotor
	4x *Solarbotics* 298:1 mini metal sealed gear motor
Power supply	1x *Pololu* step-up voltage regulator (set to 9 V)
Batteries	2x *Turnigy* 3.7 V, 750 mAh round li-po cells (total 7.4 V, 750 mAh)

2.2.1 Electronics

HyMod contains 15 custom circuit boards: 1x *processing board*, 1x *Bluetooth board*, 1x *power board*, 4x *HiGen controller*, 2x *motor driver*, 2x *encoder board*, and 4x *contact ring*. The arrangement of boards is shown in Figure 7(a).

The main microcontroller for each HyMod unit is a Teensy 3.2, a 32-bit ARM Cortex-M4 based development board running at 96 MHz. This board has built-in USB, a Controller Area Network (CAN) controller, and can be programmed with the popular Arduino development environment. The Teensy is sandwiched between the *Bluetooth board* and *processing board*; the former acts as an adapter to an off-the-shelf modem, and the latter houses additional CAN components and connects to an Inertial Measurement Unit. Figure 7(b) shows the assembled board stack.

Each HyMod unit is powered by two 750 mAh lithium polymer (li-po) battery packs (one in each module half) connected in series to give 7.4 V. The *power board* (Figure 7(c)) takes this voltage and, via a boost regulator, produces a 9 V output. This output is used to power the two *motor driver* boards, which each drive two joint motors. Additionally, to enable power sharing between modules, the *power board* passes the 9 V output through an ideal diode to create a power bus. The diode prevents the current of one power supply from feeding back in to another and potentially causing damage. The power bus is then used to produce a 5 V supply for the rest of the electronics within the module.



(a) (d)

Fig. 7 (a) Block diagram showing how the circuit boards and other components within a HyMod unit connect together. White blocks are the custom boards created for this project. Assembled (b) *processing*, (c) *power* and (d) *HiGen controller* boards are also shown.

The connectors in HyMod units are controlled using custom *HiGen controller* boards. These boards feature an ATmega324P, a motor driver, two contact switches, an analogue switch, and *contact ring* connections. The use of a separate microcontroller allows for each connector to be treated as a device on an internal communication network. Additionally, it reduces the number of connections that need to be passed through the slip rings. There are two versions of the *HiGen controller* board in each module (Figure 7(d)), one for the wheel connectors and one for the side connectors. Both boards perform the same basic functions (e.g. connector actuation, infrared proximity sensing, and neighbor communication) but differ in geometry and specialized features. For instance the wheel *HiGen controller* has a grey code disc etched into it for absolute positioning of the wheel, whereas the side controller has a RGB LED for state indication and general debugging of a module.

2.2.2 Communication

Modular systems can be thought of as computer networks, where each module acts as a node, able to communicate with other nodes. There are two main ways this can be achieved, referred to as local and global communication [21]. Local communication allows each module to communicate with its immediate neighbors, but requires that messages be relayed in order to reach modules other than direct neighbors. Global communication allows each module to send messages directly to any other module on the same network, but the identifier of the recipient must be known in advance. Due to the different use cases of local and global communication, both are implemented by HyMod. In addition, each unit features an internal I^2C network to communicate between components, with the Teensy acting as the master.

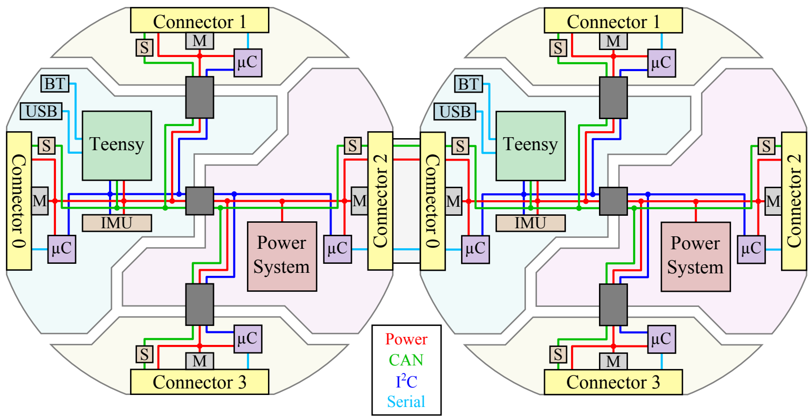


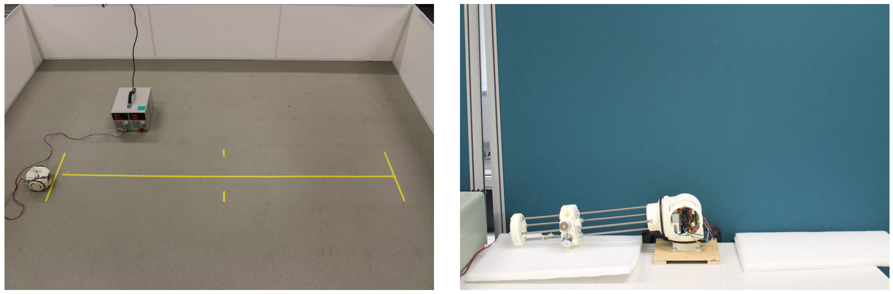
Fig. 8 The power and communication network formed between two HyMod units. BT, μC, M, and S denote Bluetooth, microcontrollers, connector motors, and bus switches, respectively.

Local communication between two HyMod units is achieved using a serial link. Messages sent from one module to another are first sent from the Teensy over I^2C to the *HiGen controller* in question. This controller buffers the message and sends it over the serial link to the neighboring module's *HiGen controller*, which stores the message until the neighboring Teensy is ready to collect it.

Global communication between HyMod units is achieved using CAN. CAN allows for multiple connected nodes to communicate with each other by broadcasting messages on a common bus. The messages are picked up by all other networked nodes, which can then act upon the data based on an identifier. By default, CAN is designed for fixed networks where there is a single line with termination resistors at the ends. Because HyMod units are self-reconfigurable, fault-tolerant CAN was used, as this places the termination resistors at each node instead. By using digital potentiometers along with FT CAN, the network resistance can be dynamically adjusted based on the number of nodes, maintaining a stable network. Additionally, to avoid looping CAN networks that get created during self-reconfiguration, HyMod employs analogue switches at its connectors to break the network. The use of these switches also allows for hybrid networks to exist [21], whereby the global network is divided in to smaller sub-networks for task processing, with local communication being used to bridge sub-networks when necessary. Figure 8 shows both the power and communication networks produced between two HyMod units.

3 Experiments

To verify the capabilities of HyMod, a single unit was used. Three main experiments were performed using the unit, examining driving speed, lifting capability and connector actuation. For the purpose of these experiments the unit was tethered to a



(a) (b)

Fig. 9 The experimental setups used for conducting (a) driving and (b) lifting experiments with a single HyMod unit, tethered to a bench power supply.

bench power supply set to 8.4 V (replicating the maximum battery voltage). Videos of the experiments can be found in the online supplementary material [26].

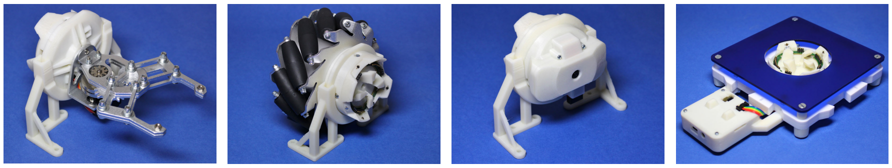
The driving speed of HyMod was determined by placing the module on the ground and timing how long it took for it to travel 2 m in a straight line. The experimental setup can be seen in Figure 9(a). The result of this experiment is that the module has a driving speed of $0.1\ \mathrm{m\ s^{-1}}$.

The lifting capability of HyMod was tested using a 3D printed variable mass holder that attaches via a HiGen connector. The holder weighs 520 g, and supports up to 1000 g (in 100 g increments) of additional weight. The distance from the center of the HyMod unit to the center of mass of the holder is 280 mm (two lattice spacings). Lifting tests were conducted by clamping the HyMod unit to a table and having its hinge joint rotate between -90 and +90 degrees (decelerating on the downward arc). The experimental setup used for these tests can be seen in Figure 9(b). The unit was tested lifting masses up to 1120 g, which is equivalent to lifting 1.8 modules in-line. Greater masses than 1120 g were attempted, but resulted in the failure of the 3D printed gears on the hinge joint's motors, followed by the docking hooks on the HiGen connectors themselves. If these components were constructed with stronger materials, the stated torque value of the motors suggests that higher lifting capacities would be achievable.

A final test was performed with HyMod, verifying that the two *HiGen controller* boards were able to operate the connectors as intended. Each connector was programmed to drive their motors between retracted and extended states every 2 s. The result was that both controller boards were able to successfully actuate the connectors. Further experiments involving HiGen can be found in [16].

4 HyMod Extensions

Unlike bespoke robotic systems made for specific tasks, modular robotic systems are intended to perform a wide variety of tasks. Some of these tasks may require



(a) (b) (c) (d)

Fig. 10 Four of the extensions created for the HyMod system: (a) Gripper extension, (b) Mecanum Wheel extension, (c) Camera extension, (d) Modular Surface extension. (a), (b), and (c) are placed on a holder, which can be attached to the side of (d) to create a pick-up location.

specialized hardware, meaning that all modules in a homogeneous modular robot would need to feature this hardware in order for said tasks to be accomplished. This would increase the cost and complexity of each module. To overcome this problem, the HyMod system allows for extensions; modules built to add specialized capabilities to a modular robot. Past systems to employ extensions include [22, 23].

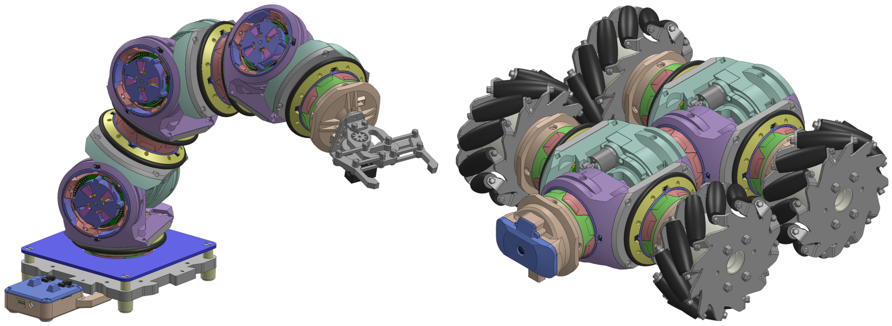
HyMod extension modules must contain processing and local communication (primarily for identification purposes), as well as at least one passive HiGen connector. A passive connector is one that is in a constant extended state, allowing for an active connector to attach to it without prior communication. This removes the need for extensions to contain their own power source. Extensions could therefore reside in known pick-up locations to be collected by modular robots when needed.

Figure 10 shows four extensions that have been developed for the HyMod system: (a) the Gripper extension uses an off-the-shelf end effector controlled by a servo motor, (b) the Mecanum Wheel extension allows for omni-directional motion when four or more are placed on a system (inspired by [24]), (c) the Camera extension uses a Raspberry Pi Zero 1.3 and Pi Cam to add video and high-powered processing to the system, and (d) the Modular Surface extension allows for square grids to be produced for modules to self-reconfigure across (inspired by [25]). The Gripper, Mecanum Wheel, and Camera weigh 220 g, 560 g, and 125 g, respectively.

Figure 11 illustrates how (a) a manipulator arm and (b) an omni-directional rover can be constructed out of combinations of HyMod units and extensions. The manipulator arm takes advantage of the 3-DOF of each unit to create a 7-DOF manipulator, with the Gripper extension mounted as the end effector. The omni-directional rover takes advantage of the two continuous rotational degrees of freedom of each HyMod unit to drive Mecanum Wheel extensions to produce motion in any direction on a flat surface. A Camera extension is mounted at the front of the rover to allow for either tele-operation or autonomous operation (e.g. object following).

5 Conclusions

This paper presented HyMod, a hybrid modular robot capable of self-reconfiguration and wheel-based locomotion. The module integrates the HiGen connector, allowing



(a) (b)

Fig. 11 Two example configurations of HyMod system modules; (a) three units and two extensions (one Gripper extension and one Modular Surface extension) forming a manipulator arm, and (b) two units and five extensions (one Camera extension and four Mecanum Wheel extensions) forming an omni-directional rover.

for single-sided disconnect and enabling units to rotate freely in place within a cubic lattice position. Details of the module were given and experiments conducted, examining the movement and lifting capabilities of a single unit. Additionally, four extensions were constructed, augmenting the capabilities of the HyMod system in the areas of manipulation, mobility, perception, and support.

Future work will involve the completion of additional HyMod units, allowing several configurations of units and extensions to be demonstrated, as well as enabling self-reconfiguration strategies to be explored.

Acknowledgments This research was funded by the Engineering and Physical Sciences Research Council (EPSRC) through scholarship support (C. Parrott) and grant no. EP/K033948/1.

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