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HiGen: A High-Speed Genderless Mechanical Connection Mechanism with Single-Sided Disconnect for Self-Reconfigurable Modular Robots

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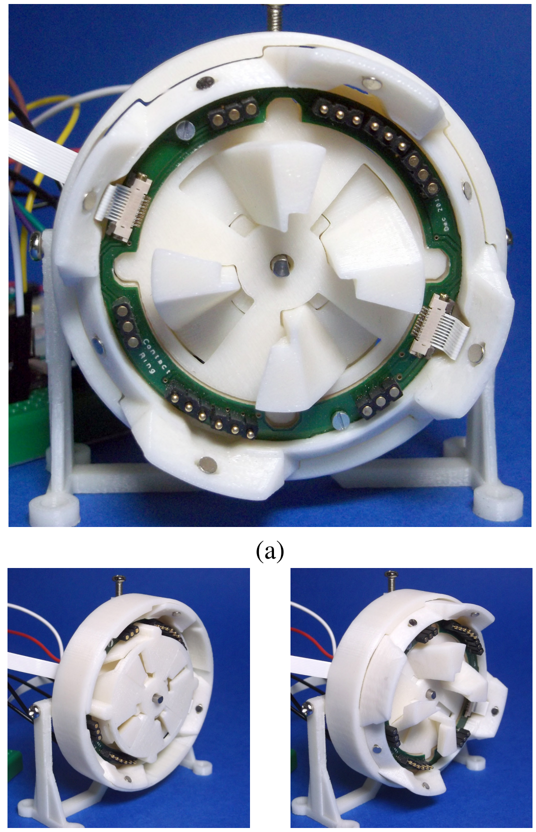
Abstract— **The practical effectiveness of modular robotic systems depends heavily on the connection mechanisms used to join their separate entities, particularly for those systems capable of self-reconfiguration. This work presents HiGen, a high-speed genderless mechanical connection mechanism for the docking of robotic modules. HiGen connectors can join with one another in a manner that allows either side to disconnect in the event of failure. During connection electrical contacts are mated, supporting the concurrent use of local and global communication protocols, as well as power sharing techniques. Rapid actuation of the mechanism allows connections to be made and broken at a speed that is, to our knowledge, an order of magnitude faster than existing mechanical genderless approaches that feature single-sided disconnect, benefiting the reconfiguration time of modular robots. The HiGen connector is intended for future work in modular robotics, but could also see use in other areas of robotics for tool and payload attachment.**

I. Introduction

The concept behind modular robotics is that rather than building a bespoke system for a given task, a kinematic approximation is assembled out of a number of ready-made entities, known as modules, instead. These modules have the advantage that they can be easily replaced when damaged or inoperable, as well as rearranged when their task or environment changes.

Modular systems can be identified as either manually reconfigurable or self-reconfigurable [1], based on the method used for connection. The former of these requires an external operation or user to separate and reattach modules, whereas the latter gives modules the ability to perform this action themselves. Self-reconfigurability presents a challenge for the field, as reliable connection mechanisms need to withstand the expected forces, provide accurate alignment, and in many cases feature inter-module communication.

This paper presents a novel 90 degree symmetric connection mechanism for self-reconfigurable modular robots, called HiGen (see Figure 1). It is capable of actuating in a short time, and features a genderless latching method that allows for independent detachment from a neighbor, without mediation. This is important for the self-repair of modular systems, as malfunctioning modules can be discarded to allow the remaining modular assembly to continue with a given task. To benefit modular systems that form lattice structures, the HiGen is capable of extending and retracting its latching mechanism as part of the actuation process, creating clearance between two neighboring modules, easing self-reconfiguration. This is demonstrated in Figures 1b and 1c. A further feature of the connector is the integration of multiple electrical pathways between connected modules, allowing for both local communication between neighbors and global communication to all modules within an assembly, as well as power transfer. These pathways are automatically made and broken as part of the extension and retraction operations. Many of these aspects have been demonstrated on systems in the past (e.g. [2], [3], [4]); however, HiGen is the first connector to combine them all into a single unit.



(a) (b) (c)

Fig. 1. The HiGen connector, shown (a) face-on, and to the side in its (b) retracted and (c) extended states.

The rest of this paper is organised as follows. Section II overviews related works in modular robotics and their connection methods. Section III details the mechanical and electrical design of the HiGen connector. Section IV presents various experiments conducted with the connector. Finally, Section V concludes this paper and discusses future work.

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TABLE I

A COMPARISON OF CONNECTORS SUPPORTING SELF-RECONFIGURATION IN MODULAR ROBOTS, WITH KNOWN ACTUATION TIMES

System / Connector	Category	Gender	Path-ways	Actuation Time (s)
ATRON [3]	Mechanical	Gendered	2	2.4
M-TRAN I/II [10]	Mag-Mech.	Gendered	3	60 to 180
M-TRAN III [11]	Mechanical	Gendered	5	5
DRAGON [2]	Mechanical	Bi-gendered	12	0.2
Roombots [12]	Mechanical	Bi-gendered	0	2
SMORES [13]	Mag-Mech.	Bi-gendered	0	0.8 to 2.3
Pebbles [14]	E.-Magnetic	Genderless	1	0.0003
RoGenSiD [15]	Mechanical	Genderless	2	12
SINGO [4]	Mechanical	Genderless	0	25
HiGen	**Mechanical**	**Genderless**	**12**	**0.2**

II. RELATED WORK

Over the past 25 years, many modular robotic platforms and connection mechanisms have been developed, expanding upon initial investigations on the CEBOT [5] platform. This has led to a variety of solutions to the connection problem, ranging from techniques for manual reconfiguration via locking [6], friction [7] and magnets [8], to controlled operation for self-reconfiguration. The majority of controllable connection mechanisms can be categorised as mechanical, magneto-mechanical or electro-magnetic. A notable exception to this is [9], which employs electro-static forces to join connectors. Additionally, these mechanisms can be sub-classed into either gendered, bi-gendered or genderless, based on how their neighboring mechanisms can connect.

- *Gendered* - Connectors that feature two distinct variants that mate together. One surface features an active element, such as a latch or electro-magnet, whilst the other contains passive elements, like posts or permanent magnets. These surfaces are typically referred to as male and female, although either one can be the active element, depending on the specific implementation.
- *Bi-gendered (hermaphrodite)* - This extension of the gendered approach combines both active and passive elements into a single connector design. Using a bi-gendered mechanism allows all connectors on a module to be identical, removing restrictions on which surfaces are able to connect together, and only needs a single side to actuate in order to make a connection. In the case of latch-based mechanisms, if both sides actuate both must disconnect in order to break the connection.
- *Genderless* - Rather than combining active and passive elements into a single design, genderless mechanisms feature active elements that mate with their neighboring active elements in such a way that either side can disconnect without action from the other.

A comparison of various connectors is shown in Table I.

A. Mechanical

A traditional approach to the connection of modules is to use a method of mechanical latching to lock them in place. A motor or other form of actuating element, such as a shape memory alloy (SMA), is used to extend hooks or clamp on to posts. Systems such as CONRO [16] and Crystalline [17] employ a gendered approach of passive posts mating with active holes, and active latches mating with passive grooves, respectively. A limitation of the CONRO design is that releasing the latch does not automatically disengage the two connectors, requiring that a separate operation be performed to pull them apart.

The M-TRAN III platform [11] uses extendible hooks to overcome the limitation of the post-hole approach. When retracted M-TRAN's connection surfaces lie completely flat with its neighbor's, allowing for translation parallel along the surface, and thus removing the need for a separate operation to pull the connectors apart. This surface-to-surface connection, whilst allowing for translation, prevents modules from rotating on axes perpendicular to the surface, requiring clearance to be gained first. This shortcoming is addressed by ATRON [18], which creates a point-to-point connection with its neighboring modules, by extending hooks a significant distance out of its active surfaces. When retracted a gap is produced sufficient for a collection of ATRON modules to rotate in place within their lattice position.

The use of hooks and latches has seen bi-gendered adaptations on a number of connectors, including CoBoLD [19] and DRAGON [2], as well as the connectors on the 3-D Unit [20], Roombots [12], and PolyBot [21] platforms. A limiting factor of these bi-gendered designs is that the latching mechanisms work independently of each other, meaning that if a connector malfunctions whilst being connected, actions taken by its neighbor will not break the connection.

Recent works have seen the creation of connection mechanisms that overcome limitations of mechanical bi-gendered designs, by offering single-sided disconnect. Only two systems exist thus far that demonstrate this capability.

The SINGO connector [4] for the Superbot platform achieves genderless latching using a chuck-like arrangement of hooks that translate in and out from a central point along the surface. This design allows an opposing connector to contract its hooks around those of the other whilst the other simultaneously expands its hooks to meet at a mid-point. If one side fails the other can actuate its mechanism in the appropriate direction to separate. Unfortunately, the use of a chuck requires mediation between connectors prior to connecting in order to assign movement roles, meaning the operation of each connector is not strictly genderless.

The RoGenSiD connector [15] for the ModRED platform [22] creates a genderless connection using a rotating plate with hooks arranged around it. This plate is able to turn in a clockwise direction relative to its surface normal to mate with an opposing connector performing the same relative operation, removing the need for prior role mediation. To prevent unwanted disconnection as a result of rotational forces, a number of posts are used to maintain alignment. These posts introduce the mentioned issues of gendered mechanical designs, by requiring an operation external to the connector to fully separate the two surfaces, which in this case relies on a translational actuator within the ModRED [22] platform on which RoGenSiD features.

B. Magneto-Mechanical

Mechanisms that employ both a mechanical actuator and permanent magnets can be considered as magneto-mechanical connectors. Their defining feature is that magnets are used to make the connection between neighboring modules, and a mechanical element is used to separate them. A well known example of this technique is on the original M-TRAN and its version II update [10]. It features north and south polarity connectors, arranged on the module such that north always aligns with south within a lattice structure, allowing connections to be automatically made when any two meet. To separate them a mechanical force is applied on the north connectors to make the magnets recede into the surface. This is achieved by the use of SMA coils that, when heated, apply a strong pulling force to overcome the strength of the magnets. Due to the properties of the SMA material used, this process can take over one minute to perform.

Another method of separating two permanent magnet connectors, as employed on the SMORES platform [13], is to use an actuating rod to hold the neighboring connector in place, whilst rotating the other. This has the advantage that all the connectors are the same, as they feature a bi-gendered arrangement of magnets, and are able to disconnect significantly faster than the SMA approach.

The M-Blocks system [23] uses a unique solution to disconnecting two module surfaces containing permanent magnets. Instead of having an actuated element on the surface, it uses an inertial mass to exert an abrupt momentum transfer onto the module, allowing it to roll from one face to another, as well as jump sections of an assembly. Using an internal actuator to produce an external force allows M-Blocks to be completely enclosed, increasing their robustness.

C. Electro-Magnetic

The use of connectors based upon electro-magnets allows for faster connection/disconnection compared to mechanical based solutions, and enables modules to be created without moving parts, potentially giving them increased robustness. Electro-magnets can be used in one of two ways; either on their own with power applied to create an attractive or repulsive force, as with Catoms [24], or combined with permanent magnets to cancel out the normal attractive force of a connection surface, as used on Molecubes [25]. The gender of electro-magnetic systems is defined primarily by their use of permanent magnets, with bi-gendered being the combination of north and south elements on a single surface.

A method for overcoming the power requirement of electro-magnets to maintain state is to employ electro-permanent magnets. These are magnets with two different materials, one of which can be influenced by an external coil.

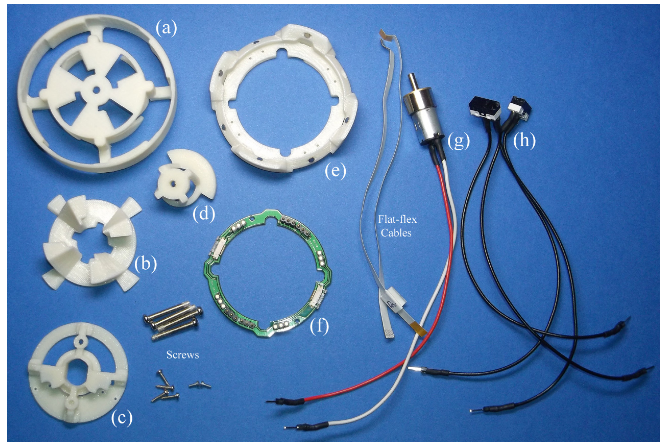


Fig. 2. A breakdown of the HiGen connector, showing the (a) housing, (b) docking hooks, (c) motor and switch mount, (d) drive shaft, (e) shroud, (f) connection board, (g) DC geared motor, and (h) contact switches.

When an electro-magnetic field is applied, the direction of one material's field is flipped to either add to or subtract from the other's field, creating a magnet that can be switched on and off. This is put into practice on the Pebbles platform [14], with magnets being placed sideways across the connection surfaces to expose both north and south poles. Placing magnets in this way allows the Pebbles to have a genderless connection surface, as either side is able to freely disconnect from the other.

III. THE HIGEN CONNECTOR

The HiGen connector consists of five 3D printed ABS plastic components, a custom connection board, a DC geared motor, two contact switches, and control circuitry. A breakdown of the connector is shown in Figure 2. The design is cylindrical, measuring 71 mm in diameter, with a depth of 32 mm at its thickest point, and 16 mm at its thinnest, with a weight of 67 g. The motor is housed directly in the center of the design and features a 298:1 gearbox, giving it a quoted speed and torque at 6 V of 79 rpm and 338 mNm, respectively. Contact switches are used to detect the connector's retracted and extended states.

A. Mechanism Details

The design of HiGen features four hooks placed radially around a central axis, with the motor rotating them between the two states. These hooks mate with an identical set of hooks on an opposing connector by passing over each other, forming a hook-to-hook relation. This arrangement enables single-sided disconnect in the HiGen design. The use of rotational latching, as opposed to translational chuck latching as in the SINGO [4], allows for the operation of two joining connectors to be identical, simplifying the control involved in creating a connection.

A shroud component is used to avoid any rotational forces around the central axis causing unwanted disconnects. This element mates with the opposing connector via the use of four protrusions, which are tapered to provide a degree of

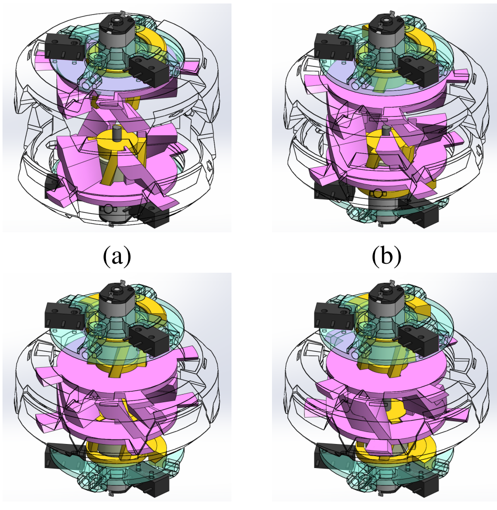


Fig. 3. Snapshots of the connection sequence of two HiGen connectors, showing the hooks (in purple) extending behind each other and locking in place. The shroud is transparent to help show the motion of the hooks.

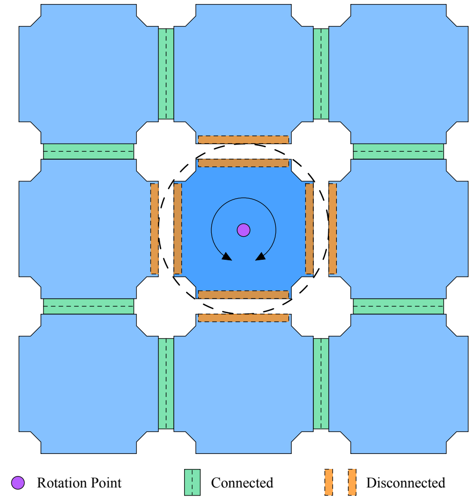


Fig. 4. A grid of square modules featuring HiGen, showing how a central module is able to rotate in place within a lattice structure, without neighbors being required to move to provide clearance.

auto-alignment. The arrangement of hooks and protrusions allow for connections at 90 degree intervals. Once two connectors are joined they can maintain a connection even when power is removed. An enclosed area is created by the shroud that prevents external manipulation of the hooks, and motor gearbox friction acts to limit any momentum transfer from indirectly separating them.

In addition to aiding alignment, the shroud also houses the connection circuit board. This features a number of spring-loaded pins (covered in more detail in Section III-B), each with a quoted force of 0.6 N at half compression, enough to cause strain on the motor. To overcome this force 8 neodymium magnets are included within the protrusion surfaces, enough to counteract the spring force but not enough to hold a connection, unlike magneto-mechanical designs. A caveat of using magnets within the shroud is that a force needs to be applied in order to electrically disconnect two joined connectors. This is automatically handled by the HiGen connector design.

To facilitate the connector's use on modules within large configurations, and to apply a disconnection force, the hooks and shroud extend out of and retract into their housing as part of the actuation process. Translation of these elements is achieved via the use of helical guides within the connector's housing, causing the hooks to spiral in and out of the mechanism. Animation steps of the process during connection are shown in Figure 3. This approach not only allows electrical contacts to be made and broken without modules being required to move, it also produces a clearance between neighbors of 12 mm. Inspiration for this functionality was taken from the ATRON [18] and 3-D Unit [20] systems, which also connect with their neighbors by extending hooks some distance above their respective surfaces. This concept, as applied to HiGen, is illustrated in Figure 4, where a central module is free to rotate within a lattice structure.

B. Electrical Details

Electrical connections between two HiGen connectors are made by a custom circuit board housed within the shroud, featuring 12 spring-loaded pins, 12 static pads, and 2 flat-flex cable connectors for interfacing with external circuitry. The flat-flex cable connectors have a maximum quoted current per contact of 500 mA, whereas the pins and pads can handle up to 3.5 A each. In total the connection board offers six wired channels between neighboring modules, all with separate incoming and outgoing pathways. The roles of these are: *Ground, Power, Connection Sense, Two-wire Global Communication* (e.g. I^2C, CAN bus), and *Local Communication* (e.g. serial). Not all of these roles require separate directional pathways, so instead the directions can be combined to add redundancy or increase current capacity, as in the case of power transfer.

To account for the four times symmetric nature of the HiGen connector, a staggered placement of contacts is used similar to that of M-TRAN III [11], but in a bi-gendered formation. In this case, the outgoing pins are duplicated by 180 degrees, and the incoming pads by 90 degrees, resulting in double the number of contacts necessary for a single orientation interval (24 versus 12). In addition to this, the incoming pads for half of the channels are 180 degrees offset from the rest to ensure that the spring-loaded contact force of two joining boards remains roughly central regardless of connection orientation. The specific placement and intended role of each contact is shown in Figure 5. Figure 6 shows how the pins and pads of two boards make contact at each orientation interval.

To perform orientation detection, the local communication channel is separated out into two outgoing and two incoming pathways (A and B). Depending on the orientation of the connection, a unique arrangement of these pins and pads is produced between one connector and its neighbor (e.g. A-A, A-B, B-A, B-B), such that only a single pathway is formed.

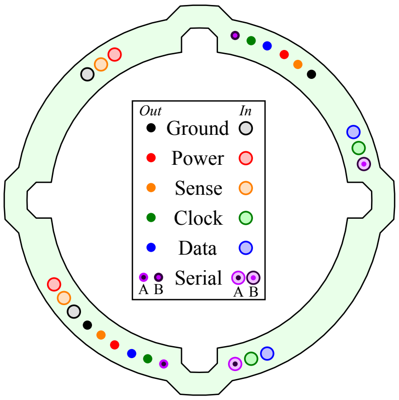


Fig. 5. The arrangement and roles of the pins (dots) and pads (circles) on the contact circuit board. Note that the local communication channel, labelled Serial, has all its pins and pads separately accessible.

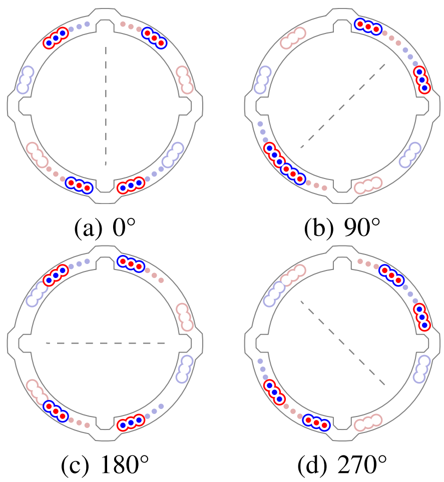


Fig. 6. An illustration of the pins (dots) and pads (circles) that make contact when two connectors are joined, at each orientation interval. The bottom board contacts (red) remain fixed while the top board contacts (blue) are flipped and rotated in a clockwise direction from (a) to (d). The dashed lines indicate the resultant mirror axes from these combined operations.

By identifying the transmitting and receiving pair of contacts the orientation between two connectors can be determined. Once identified the channel can return to being used for local communication. This is in contrast to solutions such as that on the UBot modular platform [26], which has dedicated pins that can be read to discover the orientation state.

IV. Experiments

In order to validate the HiGen connection mechanism two complete units were manufactured. The units are controlled using two separate circuits consisting of an Arduino Pro Mini 16 MHz microcontroller, a motor driver, and a number of buttons and light emitting diodes (LEDs). Power is provided by a bench supply running at 6 V, with electronics regulated down to 5 V on board each Arduino. The connectors were tested for actuation and connection time, electrical connectivity, connection repeatability, and load capacity. Figure 7 shows the setup used for conducting connection trials. A video showing the HiGen connector in operation is included in the supplementary material.

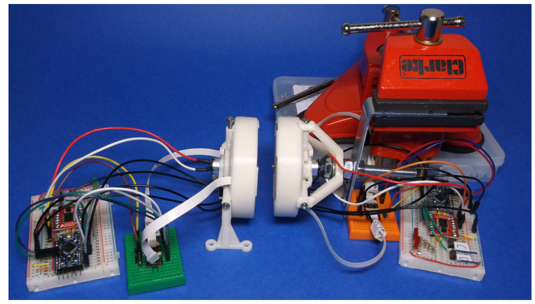


Fig. 7. The apparatus used to perform connection trials (excluding power supply and logic analyser). The left connector is free to move on the surface, whereas the right is fixed but able to rotate around the connection axis.

A. Actuation and Connection Time

To measure the transition time between the HiGen's retracted and extended states, a logic analyser was connected to the motor control lines and the two contact switches of each unit in turn. The time from the initial trigger event until the related contact switch gets pressed and settles is used as the actuation time measure.

A series of 10 actuations were conducted with each connector in isolation. The results of these trials are:

- Unit One - Average extending time 0.239 s ±0.005. Average retracting time 0.242 s ±0.003.
- Unit Two - Average extending time 0.196 s ±0.001. Average retracting time 0.189 s ±0.001.

The discrepancy between the two units' times may be attributed to differences in the surface friction of the mechanisms as a result of using 3D printing, affecting the final motor speeds when subjected to the same 6 V supply.

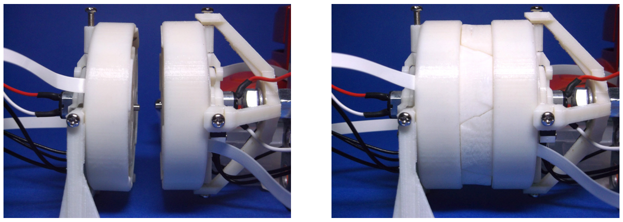
The motor within HiGen offers high actuation speed at the cost of low connection torque. To determine if this torque has any detrimental effect on the connection process the two HiGen units were connected and disconnected over a series of 10 further trials, with both units receiving a simultaneous trigger pulse. The results of these tests are:

- Unit One - Average connection time 0.252 s ±0.004. Average disconnection time 0.248 s ±0.006.
- Unit Two - Average connection time 0.198 s ±0.003. Average disconnection time 0.205 s ±0.001.

These timings show that connecting to and disconnecting from a neighboring mechanism only marginally effects the actuation time of each unit. The results demonstrate that the HiGen design is significantly faster than the existing selection of genderless mechanical connection mechanisms, and on par with the fastest bi-gendered designs.

B. Electrical Connectivity

Experiments were conducted with the two HiGen units to verify the successful connection of the electrical pathways at each 90 degree orientation interval. For this the connection sense line of each unit was wired up such that connecting with a neighbor would pull the line low. This way, either microcontroller is able to know if it is electrically connected to another mechanism even if that mechanism is not receiving



(a) (b)

Fig. 8. Two HiGen connectors being tested for connection repeatability at the designed separation distance, (a) detached and (b) connected together.

power. This is useful for situations where a tool has no internal power, and is instead powered via the connection.

Orientation detection was tested by mating the two connectors at different orientation intervals. Each Arduino microcontroller, upon detecting a connection via the sense line, initiates a transmission along both its serial communication lines. The other microcontroller then determines its orientation by detecting which message is received on which pathway. For instance, if message A is received by input B then the connectors are 90 degree offset from each other. The microcontrollers are then able to communicate via the connected input and output pathways, until they detect a connection being broken. Reconnection automatically initiates the orientation detection routine.

C. Connection Repeatability

The two HiGen units were brought together to test their ability to connect under different alignment conditions. Initially 10 trials were conducted with both units actuating simultaneously, to test the designed separation distance of 12 mm (see Figure 8). This presents the well aligned case, and was successful for 100% of the trials. An additional 10 trials were conducted at a closer distance of 6 mm to verify the connector's ability to push its neighbor towards the designed separation distance, with all being successful.

To test the connector's ability to handle other forms of misalignment, Unit One was placed in its extended state, whilst Unit Two repeatedly connected to it. The misaligned cases considered here are detailed in Figure 9. A connection was deemed to be a success if the two units fully joined together and were able to exchange handshake messages, as indicated by LEDs illuminating on both microcontroller boards. 200 misalignment trials were conducted in total. Table II shows the success of these trials, and includes the earlier 20 trials. Note that resetting the experiment after each misalignment trial involved the single-sided disconnect of Unit Two from Unit One.

D. Load Capacity

A final test was performed on the HiGen connector to determine its load carrying capacity. This was achieved by connecting the two units together, suspending them in a vertical orientation and hanging a mass below. A spring balance was used to measure the load. During this test the connectors were disconnected from the bench power supply, due to limited cable length to the microcontrollers.

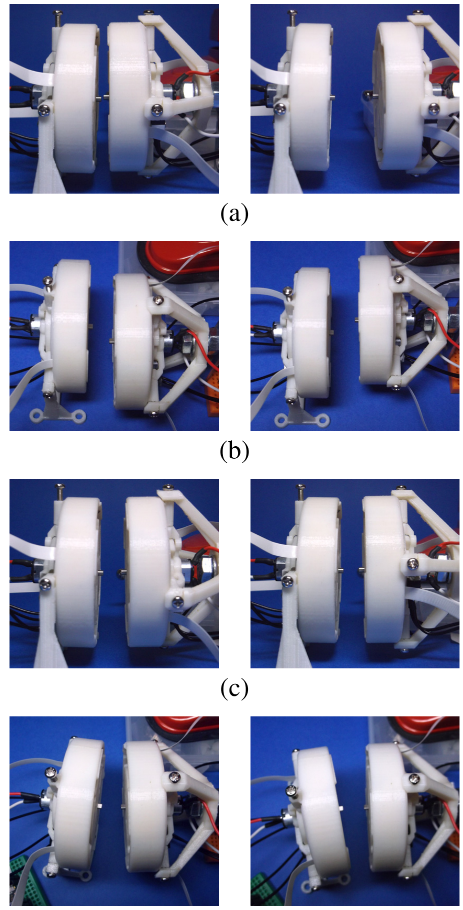


Fig. 9. Four ways two HiGen connectors may be misaligned: (a) parallel translation, (b) perpendicular translation, (c) roll rotation, (d) yaw rotation. Each pair of images shows the range of misalignment tested. Unit One is on the left, and Unit Two is on the right of each image.

The combined assembly of two connectors and mounting hardware weighed 145 g. When suspended, it was capable of supporting a load at the limit of the measuring instrument, which was 2 kg. Although this is not a thorough test of the load capacity of the mechanism, it gives an indication that 3D printed parts are already suitable for use on connectors. If the mechanical parts were made of metal, the load carrying capacity of the HiGen mechanism could be further increased.

V. Conclusions

This paper presented HiGen, a new mechanical genderless connection mechanism for self-reconfigurable modular robots. Its genderless design allows for single-sided disconnect, benefiting the self-repair capabilities of modular systems. HiGen is the fastest connection mechanism of its kind, minimising the time taken for modules to connect and disconnect when performing complex self-reconfigurations. It features multiple electrical pathways, enabling the concurrent use of several communication protocols as well as power sharing techniques. Furthermore, HiGen is the only genderless connector in which latching elements are able to retract into the mechanism to create clearance for modules

TABLE II

RESULTS OF PERFORMING MISALIGNMENT TRIALS ON HIGEN

Test	Parameter	Successes
Parallel Translation	6.0 mm	10 of 10
Well Aligned	12.0 mm	10 of 10
Parallel Translation	13.5 mm	10 of 10
Parallel Translation	15.0 mm	6 of 10
Parallel Translation	16.5 mm	5 of 10
Parallel Translation	18.0 mm	0 of 10
Perp. Translation	+5.0 mm	1 of 10
Perp. Translation	+2.5 mm	4 of 10
Perp. Translation	-2.5 mm	3 of 10
Perp. Translation	-5.0 mm	0 of 10
Roll Rotation	+12°	2 of 10
Roll Rotation	+8°	9 of 10
Roll Rotation	+4°	10 of 10
Roll Rotation	-4°	10 of 10
Roll Rotation	-8°	9 of 10
Roll Rotation	-12°	3 of 10
Yaw Rotation	+15°	3 of 10
Yaw Rotation	+10°	10 of 10
Yaw Rotation	+5°	10 of 10
Yaw Rotation	-5°	10 of 10
Yaw Rotation	-10°	9 of 10
Yaw Rotation	-15°	2 of 10

to translate or rotate in place within a lattice structure. Two full prototypes were built, and over 200 trials conducted to validate their capabilities.

Future work will incorporate the HiGen connector into a new modular robotic platform currently under development, whereby self-reconfiguration strategies will be explored to demonstrate the connector's effectiveness.

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REFERENCES

[1] K. Støy, D. Brandt, and D. J. Christensen, *Self-reconfigurable robots: An introduction*. The MIT Press, 2010.

[2] M. Nilsson, "Connectors for self-reconfiguring robots," *IEEE/ASME Transactions on Mechatronics*, vol. 7, no. 4, pp. 473–474, 2002.

[3] M. W. Jorgensen, E. H. Østergaard, and H. H. Lund, "Modular ATRON: Modules for a self-reconfigurable robot," in *Proceedings, IEEE/RSJ International Conference on Intelligent Robots and Systems*, vol. 2, 2004, pp. 2068–2073.

[4] W.-M. Shen, R. Kovac, and M. Rubenstein, "SINGO: A single-end-operative and genderless connector for self-reconfiguration, self-assembly and self-healing," in *Proceedings, IEEE International Conference on Robotics and Automation*, 2009, pp. 4253–4258.

[5] T. Fukuda, S. Nakagawa, Y. Kawauchi, and M. Buss, "Self organizing robots based on cell structures - CEBOT," in *Proceedings, IEEE International Workshop on Intelligent Robots and Systems*, 1988, pp. 145–150.

[6] J. Davey, J. Sastra, M. Piccoli, and M. Yim, "ModLock: A manual connector for reconfigurable modular robots," in *Proceedings, IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2012, pp. 3217–3222.

[7] V. Zykov, A. Chan, and H. Lipson, "Molecubes: An open-source modular robotics kit," in *Proceedings, IROS Self-Reconfigurable Robotics Workshop*, 2007.

[8] A. Lyder, R. F. M. Garcia, and K. Støy, "Genderless connection mechanism for modular robots introducing torque transmission between modules," in *Proceedings, ICRA Workshop on Modular Robots, State of the Art*, 2010, pp. 77–81.

[9] M. E. Karagozler, J. D. Campbell, G. K. Fedder, S. C. Goldstein, M. P. Weller, and B. W. Yoon, "Electrostatic latching for inter-module adhesion, power transfer, and communication in modular robots," in *Proceedings, IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2007, pp. 2779–2786.

[10] H. Kurokawa, A. Kamimura, E. Yoshida, K. Tomita, S. Murata, and S. Kokaji, "Self-reconfigurable modular robot (M-TRAN) and its motion design," in *Proceedings, 7th International Conference on Control, Automation, Robotics and Vision*, vol. 1, 2002, pp. 51–56.

[11] H. Kurokawa, K. Tomita, A. Kamimura, S. Kokaji, T. Hasuo, and S. Murata, "Distributed self-reconfiguration of M-TRAN III modular robotic system," *The International Journal of Robotics Research*, vol. 27, no. 3-4, pp. 373–386, 2008.

[12] A. Spröwitz, R. Moeckel, M. Vespignani, S. Bonardi, and A. Ijspeert, "Roombots: A hardware perspective on 3D self-reconfiguration and locomotion with a homogeneous modular robot," *Robotics and Autonomous Systems*, vol. 62, no. 7, pp. 1016–1033, 2014.

[13] J. Davey, N. Kwok, and M. Yim, "Emulating self-reconfigurable robots-design of the SMORES system," in *Proceedings, IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2012, pp. 4464–4469.

[14] K. Gilpin, A. Knaian, and D. Rus, "Robot pebbles: One centimeter modules for programmable matter through self-disassembly," in *Proceedings, IEEE International Conference on Robotics and Automation*, 2010, pp. 2485–2492.

[15] S. G. M. Hossain, C. A. Nelson, and P. Dasgupta, "RoGenSiD - A rotary plate genderless single-sided docking mechanism for modular self-reconfigurable robots," in *Proceedings, ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, 2013, p. V06BT07A011.

[16] A. Castano, A. Behar, and P. M. Will, "The Conro modules for reconfigurable robots," *IEEE/ASME Transactions on Mechatronics*, vol. 7, no. 4, pp. 403–409, 2002.

[17] D. Rus and M. Vona, "Crystalline robots: Self-reconfiguration with compressible unit modules," *Autonomous Robots*, vol. 10, no. 1, pp. 107–124, 2001.

[18] E. H. Østergaard, K. Kassow, R. Beck, and H. H. Lund, "Design of the ATRON lattice-based self-reconfigurable robot," *Autonomous Robots*, vol. 21, no. 2, pp. 165–183, 2006.

[19] J. Liedke and H. Wörn, "CoBoLD - A bonding mechanism for modular self-reconfigurable mobile robots," in *Proceedings, IEEE International Conference on Robotics and Biomimetics*, 2011, pp. 2025–2030.

[20] S. Murata, H. Kurokawa, E. Yoshida, K. Tomita, and S. Kokaji, "A 3-D self-reconfigurable structure," in *Proceedings, IEEE International Conference on Robotics and Automation*, vol. 1, 1998, pp. 432–439.

[21] M. Yim, K. Roufas, D. Duff, Y. Zhang, C. Eldershaw, and S. Homans, "Modular reconfigurable robots in space applications," *Autonomous Robots*, vol. 14, no. 2-3, pp. 225–237, 2003.

[22] J. Baca, S. Hossain, P. Dasgupta, C. A. Nelson, and A. Dutta, "ModRED: Hardware design and reconfiguration planning for a high dexterity modular self-reconfigurable robot for extra-terrestrial exploration," *Robotics and Autonomous Systems*, vol. 62, no. 7, pp. 1002–1015, 2014.

[23] J. W. Romanishin, K. Gilpin, and D. Rus, "M-Blocks: Momentum-driven, magnetic modular robots," in *Proceedings, IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2013, pp. 4288–4295.

[24] B. T. Kirby, B. Aksak, J. D. Campbell, J. F. Hoburg, T. C. Mowry, P. Pillai, and S. C. Goldstein, "A modular robotic system using magnetic force effectors," in *Proceedings, IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2007, pp. 2787–2793.

[25] V. Zykov, E. Mytilinaios, M. Desnoyer, and H. Lipson, "Evolved and designed self-reproducing modular robotics," *IEEE Transactions on Robotics*, vol. 23, no. 2, pp. 308–319, 2007.

[26] S. Tang, Y. Zhu, J. Zhao, and X. Cui, "The UBot modules for self-reconfigurable robot," in *Proceedings, ASME/IFToMM International Conference on Reconfigurable Mechanisms and Robots*, 2009, pp. 529–535.