The X-CLAW Self-Aligning Connector for Self-Reconfiguring Modular Robots (Extended Abstract)

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***Abstract*— Inter-module connectors are one of the key components of self-reconfiguring robot modules. Connectors provide the autonomous attaching and detaching that make self-reconfiguration possible. Robust connector design must consider the uncertainty in module positioning that is inherent to any physically realized system. We are interested in connectors that use mechanical self-alignment to tolerate the inevitable module misalignment that arises from such uncertainty. In this extended abstract, we divide the problem of connector design into two subproblems, grasping/self-alignment, and latching, and present the intial design and hardware evaluation of a new connector, the *X-CLAW*.**

I. Introduction

One of the most important mechatronic elements of a modular robot system is the inter-module connection or linkage mechanism. *Connectors* are particularly important for self-reconfiguring (SR) modular robots since they implement the autonomous attaching and detaching characteristic of this type of robot. Physical realization of SR robots requires robust, dependable connectors. We are interested in the design and evaluation of robust connectors, and in particular in the ability of connectors to mechanically *self-align*.

Motivation for studying connector design, and especially the property of self-alignment, stems from the desire to build large SR robots in hardware. This goal is well-known to the modular robots research community [1]. Although many challenges remain in building systems with many modules, the problem of connector self-alignment is particularly salient. There is inherent uncertainty in module pose during attachment, and this uncertainty must be considered at a fundamental level. Because the goals of module design tend towards simple, low-DOF modules, it is critical to address the problem of handling this uncertainty through mechanical self-alignment.

The most important challenge in designing a self-aligning connector is how to incorporate large tolerance for misalignment within the space constraints of the module enclosure. One strategy for overcoming pose uncertainty is to use large mechanical components that protrude to maximize the size of the "region of reachability" surrounding the connector. However, these mechanical components must be stowed within the volume of the module when not actively connecting. Other widely accepted design challenges include hermaphroditic connectors, strength of latching, how to route power and communication through the connectors, connection invariant to relative rotation of modules, and minimizing power consumption.

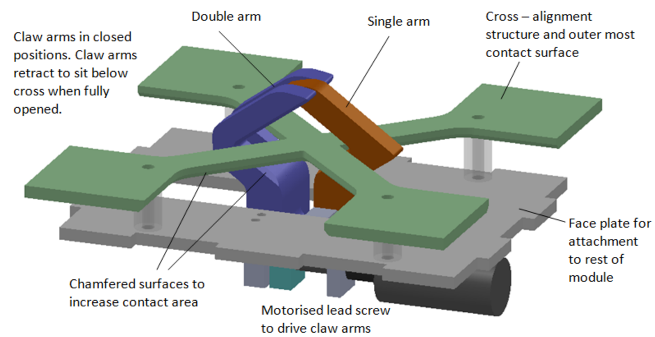


Fig. 1: The X-CLAW connector design.

Our approach is to divide the connector design problem into two distinct subproblems by separating grasping/alignment from latching. Latching is well-studied and several connectors have been developed with very good latching performance [2], [3], [4], [5]. We approach grasping and self-alignment by designing the connector essentially as a two-fingered gripper. When attaching, the gripper fingers grasp an attachment structure on the neighbor connector and pull it tight. The attachment structure conceptually is composed of two perpendicular rods that form an "x" or cross shape. This design aligns the two connectors as the fingers slide along the rods and approach the center of the cross structure. Although one connector is active and the other passive, the design is still genderless (hermaphroditic) because all connectors contain both active and passive components. Grippers extend for the active role and retract for the passive role. Fig. 1 illustrates a single connector, with both gripper and attachment structure visible.

The attachment structure has 4-way rotational symmetry, which allows connection at 90-degree increments of relative rotation. This is sufficient for lattice-based modules that occupy a cubic lattice. Power is consumed during connection only because once latched, the two modules are mechanically clamped as is typical of most existing connector designs. We ignore the problem of integrating wired or IR communication hardware because we favor RF communication [6]. We do not address the issue of power transmission; we assume each module includes its own power source.

In this extended abstract, we present the design and initial hardware prototype of the X-CLAW connector. We provide results of basic performance evaluation in self-alignment and latching. To conclude, we briefly discuss the open problem of how to develop a common metric for evaluating self-alignment performance.

II. Related Work

Many connector designs have been proposed for modular robots, using a variety of design strategies that range from permanent or electro- magnets [7], [8] to mechanical latches [9]. A nice survey of these strategies can be found in [2]. We focus on mechanical strategies related to gripping or hooking in this section.

The Molecule robot [10] proposes a male/female design based on a 4-fingered gripper. Fingers on the male connector attach to hook points on the female connector. The ATRON module [2] employs finger-like hooks that attach to rods on the neighboring connector. This design is shown to have high latching strength.

The M-TRAN module [3] has hook-based connectors, where hooks rotate to clamp together the faces of connecting modules. The hook design can be viewed as a gripper design with very short fingers. Tolerance to misalignment normal to the connector is limited by the length of the hooks. However, this design achieves high clamping force. The Roombots module [4] improves the hook design through shaped grooves in the passive face. The hooks slide along the sides of the wedge-shaped grooves to correct for rotational misalignment.

The SINGO connector [11] has four wedge-shaped jaws that travel on perpendicular rails. During connection, the jaws move from the outer corners of the module face towards its center. The shape of the jaws is designed to tolerate misalignment. Tolerance to normal misalignment is limited by the height of the jaws normal to the module face.

III. Connector Design

The design of X-CLAW was shown earlier in Fig. 1. The connector utilises a two-fingered gripper, or *claw*, closing on opposite angles of a cross-shaped structure to achieve alignment. The claw arms rely on circular motion to grip and pivot around points on the inner frame below the cross. The arms move from an open position of being completely retracted to a closed position of maximum extension. The arms are configured in a three prong arrangement – two prongs opposing one prong to improve stability in gripping. These will be referred to as double arm and single arm respectively. The arm profile mimics that of a prismatic jaw. The cross makes up one of the outer faces of the module, functioning as the contact surface to an adjacent module and the thin arms of the cross taper out into square panels towards the corners to increase the contact area.

The claw arms are driven by a DC motor connected to a leadscrew assembly. The linear motion is applied to lengths of the arms which extend below their connected pivot points,

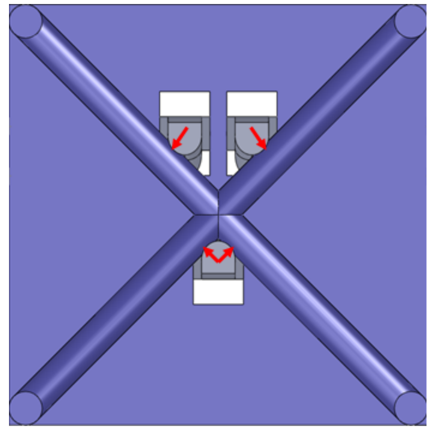


Fig. 2: Claw-cross arrangement: vertically opposite forces applied by arms to cross forcing the cross to center.

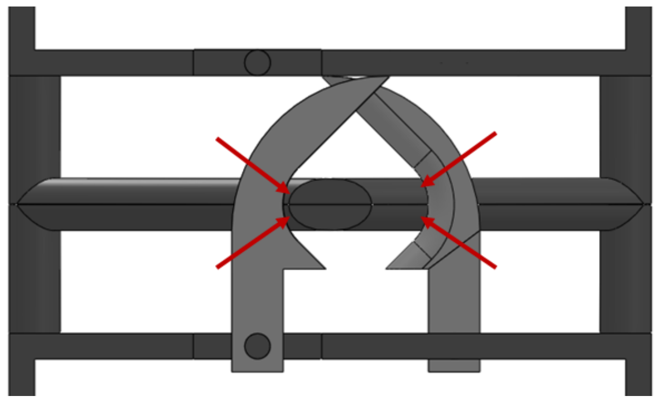


Fig. 3: Claw prismatic profile in contact with complying surface on cross: the horizontally applied forces are translated into a vertical ones, compressing the contacting crosses together.

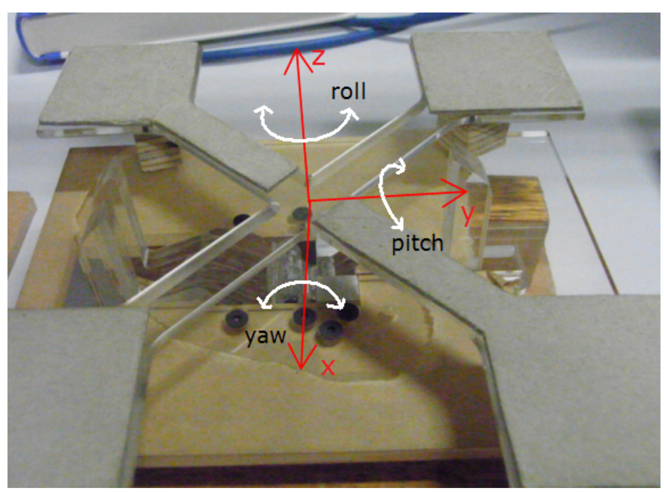


Fig. 4: Connector prototype and the six degrees of freedom in connection: three lateral, three angular.

generating the circular motion required to close the arms. The double arm is connected to the leadscrew nut by a connecting rod, while the single arm takes motion from the movement of the double arm via another connecting rod. Due to the changing distances between the connecting rod points connecting the two arms during operation, the arms do not close at the same rate. However, in fully open and fully closed positions, the arms are parallel to each other.

Each connector is able to function as either a master or a slave, thus all connectors are homogeneous. During connection, the master connector is actively gripping with its claws while the slave connector essentially functions as clawless face. When two connectors are within docking range, the master connector claws close onto the slave cross. As the arms close, the arm contours simultaneously force the slave connector closer to the master connector and also center the two connectors to each other. See Figs. 2, 3, and 4. No energy is used once connected.

The present design offers several main benefits. These include: 1) high compliance enabling it to correct for substantial amounts of misalignment, 2) homogeneity, allowing any two connectors to dock together, and 3) can connect in four 90-degree orientations.

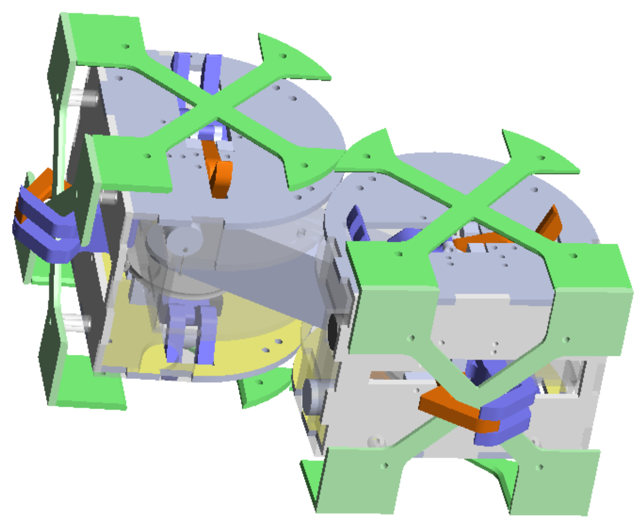


Fig. 5: CAD model of test module with six connectors installed.

IV. Hardware Prototype

In order to validate the X-CLAW design in hardware, we constructed an oversized prototype module with X-CLAW connectors. Kinematically, the prototype module is an MTRAN/SUPERBOT-style, 3 DOF (3R) module [3], [12].

Fig. 5 shows a CAD model of the prototype. The connecting faces have 157 mm edges. Each connector fills an entire outer surface of the module, taking up a maximum depth of 57 mm. The connectors on the side faces of the module have semicircular edge on one half to allow for rotation.

The body of the module is constructed using laser-cut acrylic. For testing, three active connectors were installed: one on each end face and one on one of the side faces. Active connectors are labelled in Fig. 6. The module is controlled by a microcontroller (ARM Cortex) with each individual DOF and connector commanded manually through a GUI running on a desktop computer.

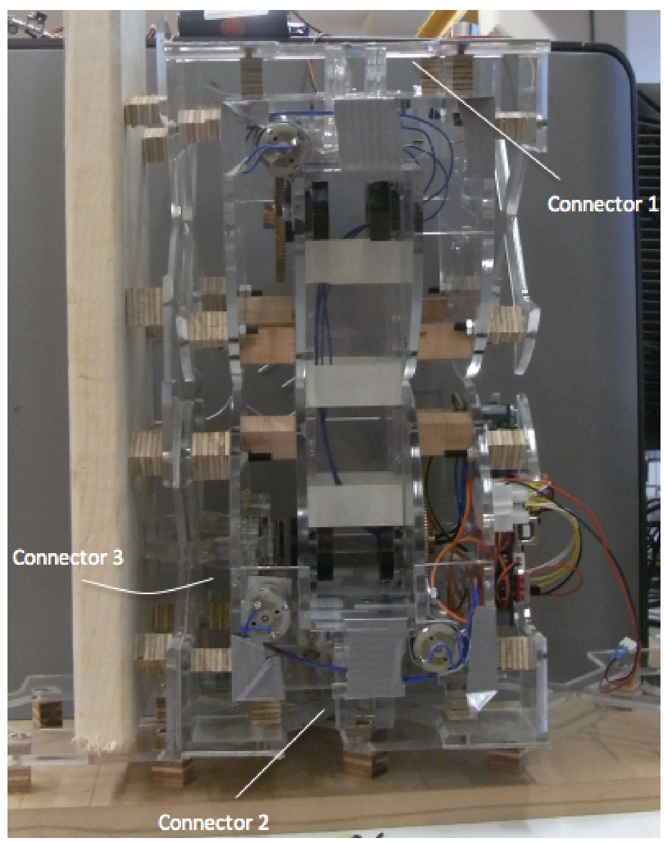


Fig. 6: Test module with three active connectors installed. This is sufficient to perform tests demonstrating compliance and strength.

V. Performance in Compliance

The master connector has six DOF when approaching the slave connector. The coordinate frame attached to the connector is labelled in Fig. 4: lateral misalignment in the x and y axes, normal misalignment in the z axis (separation), and angular misalignment in the x and y axes (pitch/yaw), and in the z axis (roll). It is designed to have adequate compliance in all. Misalignment was measured from the center of the most outward surface of the connector.

In the case of our connector, compliance comes from the shape of the cross and the shape and arrangement of the arms. Lateral misalignment in the x and y directions and angular misalignment along the z axis is corrected by the squeezing force that, applied by arms in the given arrangement, force the slave cross to move until it is central

TABLE I: Comparison of simulated and physical results of maximum lateral gripper compliance.

Axis	Simulated (mm)	Physical (mm)
x	20.25	18
y	30.17, -32.89	21, -24
z	18	16

TABLE II: Comparison of simulated and physical results of maximum angular gripper compliance.

Axis	Simulated (deg)	Physical (deg)
x	11.1, 12.64	6+
y	14.15	6+
z	22	21

to the master connector in order to reach equilibrium. Lateral misalignment in the z direction is corrected by the shape of the arms. The incline of the arms, upon closing, force the the slave cross to move closer to the master cross until they are pressed together. Angular misalignment in the x and y axes occur in conjunction with some degree of separation and similarly relies on the arm shape to align.

Compliance in each of these DOF can be analysed based on the geometry of the connector components. In the x axis, maximum lateral compliance is constrained by the distance from center of the outer edge of the double arm and the distance from center of the flat side surface of the broad corner squares. In the y axis, maximum lateral compliance is determined by the largest distance from the center of the inner prism edge of the arms when extended above the master cross and the smallest distance from the center of the slave cross that it contacts.

Because compliance in pitch and yaw do not occur independently of separation, maximums were harder to define. In order to measure compliance we measured each dimension of misalignment independently. The connectors were separated by a measured distance, keeping the axes of rotation parallel to each other along the z axis and allowing for two DOF in the axis of pitch or yaw and laterally along z.

Maximum compliances in all DOF were measured with models in CAD simulation (SolidWorks 2008) and with physical tests. Physical tests were performed with individual connector prototypes not installed into a module. A jig was built to suspend the master connector above the slave connector in a fixed position. The master connector could be adjusted for rotation along axes x and y while the slave gripper below it could be adjusted in the four remaining DOF and was free to move throughout connection. Discrete positions were tested to find the maximum misalignment in each DOF that the connector was able to overcome and achieve connection. Tab. I and Tab. II show the measured results.

Because actual misalignment is usually more complex and simultaneously involves deviations in many, if not all, degrees of freedom, compliance in individual DOF provide

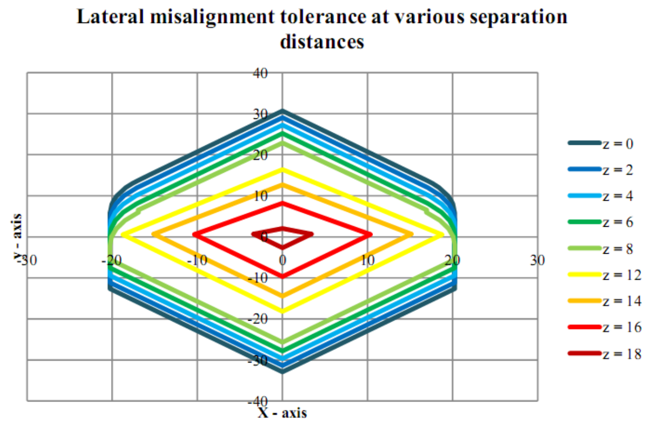


Fig. 7: Simulated results of combined lateral misalignment showing compliance within a dome-like volume. Units in mm.

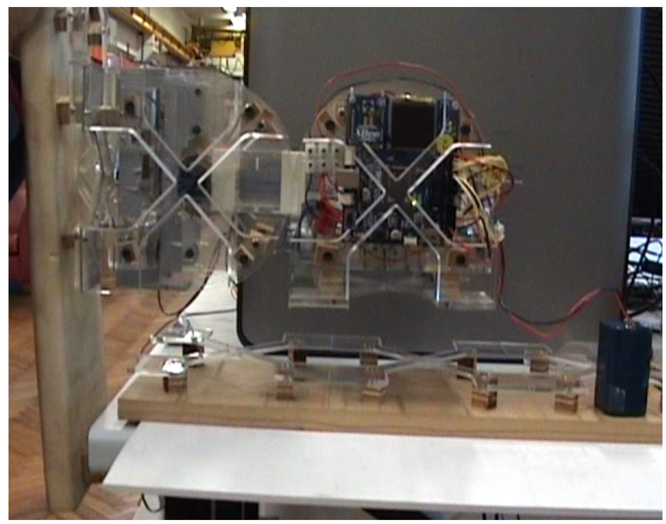
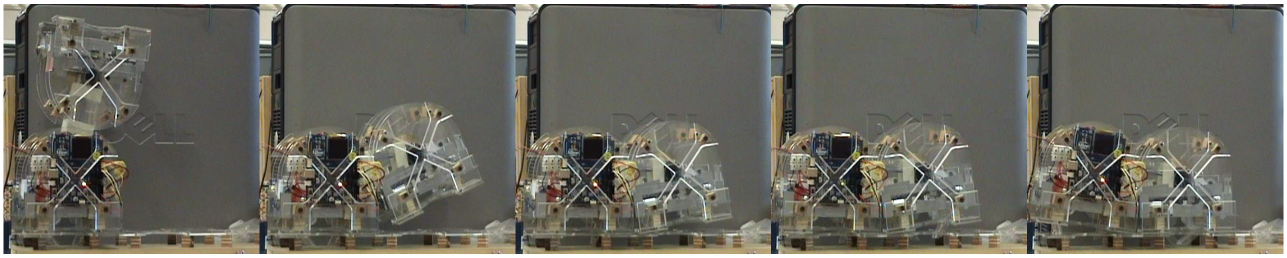


Fig. 8: Retention testing of the connector in one of the more challenging configurations to maintain connection for due to the large moment arm.

only an idea of best case scenarios. Some simulated situations with combined misalignment were performed with CAD models (SolidWorks 2008 using the Move Components function with Physical Dynamics enabled). One connector was fixed while the other was placed free in discrete positions with varying linear offsets. Due to the arc travel path of the claw arms and the outwardly extending arms of the contact cross, the final volume that represents the tolerable linear offsets of the slave connector is dome-like (Fig. 7).

VI. Performance in Retention

Retention strength of the connector determines how much weight it will be able to support once connected. At a minimum, the connector needs to be able to support its own weight in the most challenging of configurations. The configuration with the greatest shear force and bending moment applied to the connector is when the two end connectors are perpendicularly furthest apart with only one end connected



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

Fig. 9: Test module shifting connection between connectors on simulated lattice. Angular misalignment is introduced by artificially limiting joint range.

to another module and the whole module is horizontal, essentially forming a cantilevered beam, as shown in Fig. 8. A number of other configurations were also tested. The total mass of our test module was $2.73\ kg$. The connector was able to support this mass in all tested configurations. It should be noted that this is only a preliminary measurement as the test module is intentionally oversized to aid in construction and testing.

VII. Whole-Module Testing

The main goal of this connector design is for it to have substantial compliance enabling reliable self-reconfiguration. Using the test module described in Sec. IV, we were were able to test its ability to correct misalignment produced by positioning errors that are anticipated to occur during self-reconfiguration. The test module was commanded to move around on a panel of connector crosses which simulated a group of modules assembled in a lattice (Fig. 9). Due to small protrusions of motors outside the module body, the half modules were unable to sit fully flush against each other in some configurations, thus creating greater misalignment than we would usually expect to encounter under standard module function. The connectors were able to consistently correct this demonstrating its high compliance and potential for self-reconfiguration. This was only a preliminary test and further testing is needed to determine the connector's reliability.

VIII. Lessons Learned

In evaluating this first prototype of the X-CLAW, we observed some problems in connection. Predominantly this was the relatively loose grip (low clamping force) the master connector exerted on the slave cross. Up to $6\ mm$ of lateral freedom was measured at the corners, shown in Fig. 10. Other problems encountered were the aforementioned motor protrusions, component weakness and occasional failure. These were attributed mostly to inadequate manufacturing methods that resulted in lack of precision in components and their positions as well as material compliance. We are currently designing a second prototype that addresses these problems.

IX. Conclusions and Future Work

We have presented the X-CLAW design and hardware prototype. Our initial evaluation shows that the physical performance validates simulated performance and shows promising results for self-alignment and latching. We plan to continue hardware validation and further refine the design of the gripper shape and actuation mechanism.

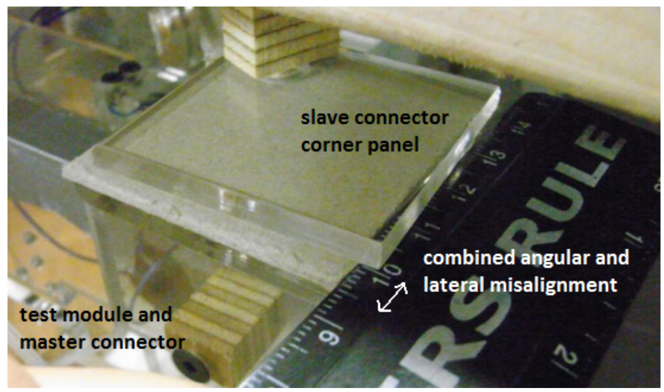


Fig. 10: Observed translational freedom between docked connectors. Maximum offset of $6mm$ was measured at corners.

An open question for future work is the need for developing a common evaluation methodology for comparing connector performance. We measured performance for translational and rotational misalignment independently, but it is interesting to ask how to best measure misalignment tolerance in general. Ideally we would like to develop a "reachability index" that allows direct comparison of various connector designs.

Acknowledgments

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