Highly Compliant and Self-Tightening Docking Modules for Precise and Fast Connection of Self-Reconfigurable Robots

Behrokh Khoshnevis*, Peter Will and Wei-Min Shen
Information Sciences Institute
4676 Admiralty Way, Marina del Rey, CA 90292, USA
Industrial & Systems Engineering *
University of Southern California
khoshnev@usc.edu, {shen,will}@isi.edu

Abstract — **This paper describes a new docking system called Compliant-And-Self-Tightening (CAST) developed as an effective and efficient connector for joining and releasing modules of self-reconfigurable or metamorphic robotic systems. CAST has been successfully implemented in CONRO where its highly compliant and passive features have allowed a considerable ease of execution of a variety of docking algorithms, while using no additional energy for docking and negligible amount of energy for undocking. Development of CAST was motivated by observing the difficulty of implementation of an earlier less compliant docking system designed by the authors for CONRO.**

1. INTRODUCTION

Docking between multiple components is a basic problem that occurs in almost all engineering systems that must dynamically change their structures for various purposes. Human-operated docking is widely seen in daily life, and can be as simple as changing a blade in a razor or as complex as docking one spacecraft to another.

In comparison with human-operated docking, autonomous docking is a more difficult problem. For example, two satellites docking in space may take many hours to align approach, dock and secure. In many engineering domains, conditions are preset in order to make the process feasible and reliable. For example, docking among locomotives and railroad cars is an example worth looking at in detail. The cars are on rails; all rails in one country have the same width (to quite high tolerances); all cars have the same height (again to quite high tolerances); the coupling hooks are hermaphroditic and held loosely enough so that the hook on one car will slide over the hook on the second car in spite of the build-up of tolerances and then lock. Under these conditions, docking can happen automatically when two railroad cars are approaching each other on the same track with a certain speed. Under these circumstances, a simple symmetric hook linkage is sufficient for docking. Of course, simplicity is an after-the-fact observation. The actual dock that is employed is a major technical accomplishment from the era of the railroad.

Among all applications of autonomous docking, perhaps the one that demands autonomous docking the most is the self-reconfigurable or metamorphic robot. Such robots are made of many autonomous modules that self-rearrange their connections to change the robot's morphology (e.g., shape and size) in order to meet the environmental and other demands of a given task. Such robots are useful in applications that benefit from or require the use of robots with different topologies. A metamorphic robot could be a "crab" to climb over rubble and then smoothly morph to a "snake" to slither down between the stones to locate a person or some artifact. It may become a ball to roll down a hill, or transform a leg into a gripper to perform a grasping operation. Modules are usually interconnected to make a chain or tree of modules, but rings and lattices are supported also. An example of such robots, called CONRO [1,2,3] (see Figure 1) can be found at our web site http://www.isi.edu/conro. Since the task of autonomous docking in these robots is so intricate and challenging that if a reliable solution is identified, it could be applied to almost any docking domain.

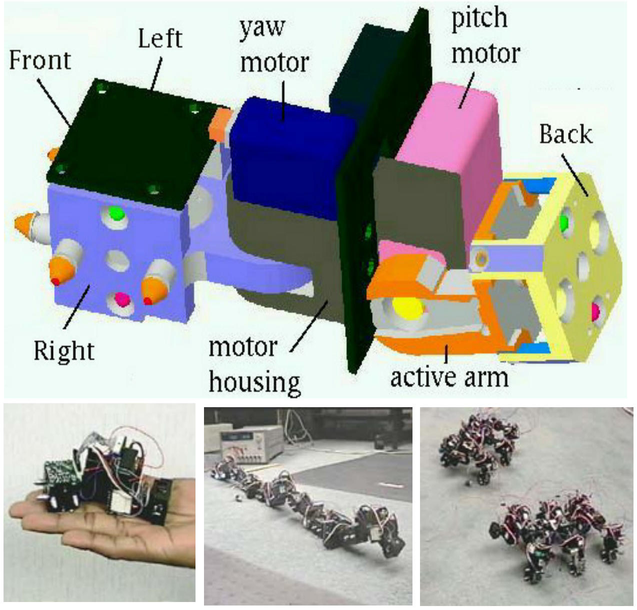


Figure 1. The CONRO metamorphic robotic

Indeed, autonomous docking is a long-standing and challenging problem for self-reconfigurable robots. The challenge lies in the fact that autonomous docking is the only ability that enables all reconfigurable actions, and it must be performed frequently and in different system configurations. Docking must be foolproof and support all of the interconnection needs of the system --- from structural load bearing to communications and power sharing. Such docking systems involve positioning the various modules correctly, then making a connection that must support as many modalities as needed in a particular application, and work in many, sometimes wet, dirty, and hostile environments. The problem of interconnection and interfacing gets much worse as the number of modalities involved increases. Furthermore, the components must make and break both multi-modal electrical and mechanical connections, in spite of being repeatedly connected and disconnected.

Autonomous docking is extremely critical for the success of metamorphic robots. Without a reliable solution to the problem, the true advantages of metamorphic robots cannot be delivered to real-world applications and will remain a mathematical exercise exciting only scientific curiosity. After nearly ten years of research by the international community, autonomous docking is commonly believed to be the most challenging problem in self-reconfigurable robots.

2. RELATED WORK

The problem of autonomous docking has been with the metamorphic robots ever since the field was established over ten years ago. Almost all existing metamorphic robots either bypass the problem (use human assistance or simulation) or simplify the problem for easy solutions. Nevertheless, many isolated docking techniques have been developed over the years. For example, Nilsson [4] has designed a 2D self-aligning docking device and traded the device's generality for the tolerance of errors. Roufas et. al. [5] have experimented with a 6D docking sensing system using Infra-Red (IR). Fukuda and Nakagawa [6] studied docking with CEBOT. Murata et. al. [7] constructed a complex mechanism for connecting arms. Bereton and Khosla [8] have used visual images as guidance for docking between mobile robots. Robot Molecules [9] first use simple magnetic or electro-magnetic connections and then a gripper connector for docking between modules. The prototypes of Polybots [10] use tele-operations to assist docking, and the Proteo robots [11] assume that a module can dock with another by "rolling over" onto that module. In most of these approaches, autonomous docking is assumed to be a local action and does not involve modules that are not to be docked.

Chen [12] describes a theory of docking and the desirable attributes of a docking system, Barnes [13] distinguishes various kinds of robotic docking in terms of the number and type of degrees of freedom required in the task. Atkins and Murphy [14] describe the need for the final position and orientation of the robot to be attainable in spite of the tolerance build-up. This led to the notion of active methods for high precision docking. High-precision docking is often performed using special purpose hardware, such as ultrasonics [15], light emitting diodes (LEDs) as in CONRO, range-finding devices, or vision. There is a large literature on visual servoing. Its application to docking is described in [14, 16, 17]. Visual servoing is used in reactive docking procedures by centering on a target image, moving towards it in a known manner, re-centering and iterating. Mandel and Duffie [16] describe a visual system used in factory applications.

What is not discussed in detail in the literature is the whole area of accommodating for tolerances. Also not discussed as a part of the docking problem, apart from the work of Shen and Will [1], is the control of mutual relative motion of both of the target areas.

These examples show enough of the problem to allow some generalizations. Nilsson [18] has surveyed the robotic docking art and classified forms of connectors and desirable properties. The classification includes geometry, latching, physical robustness, energy transfer, maintenance, manufacturing and materials. He defined docking connectors as *symmetric* or *asymmetric* (i.e. what is their parity); *polycrystalline* which are systems on a crystalline lattice that operate by disconnecting and reconnecting and thus reconfigure in order to move; *polymeric,* where there are chains of identical modules; *monomeric,* where only a few modules can interconnect; or *gaseous*, where only two modules can interconnect. Nilsson categorizes our prior work on connectors in CONRO as asymmetric and polymeric.

3. PAST CONRO DOCKING EXPERIENCE

We first designed a docking system activated by shaped memory alloy (SMA) wire and used it daily in experiments on reconfiguration for two years. As shown in Figure 2, the locking mechanism of in the docking module is located at the back of the facet. The main component is a thin metal blade (the dark, S-shaped piece at the center) that can rotate around the center shaft. The two curve-shaped tips of this blade are positioned at the back of the docking holes. The position of the blade is biased toward locking position by spring force. When a docking pin enters the hole, the flexible blade snaps into the groove of the pin, locking it into position. To unlock the pins, the blade is

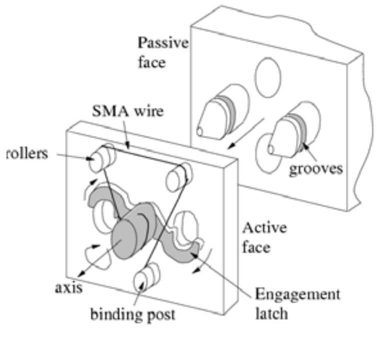


Figure 2. First generation CONRO docking system

pulled back by a SMA wire so that the blade disengages the groves of the pins and releases the pins to be pulled away. For a more detail description of this design refer to [3].

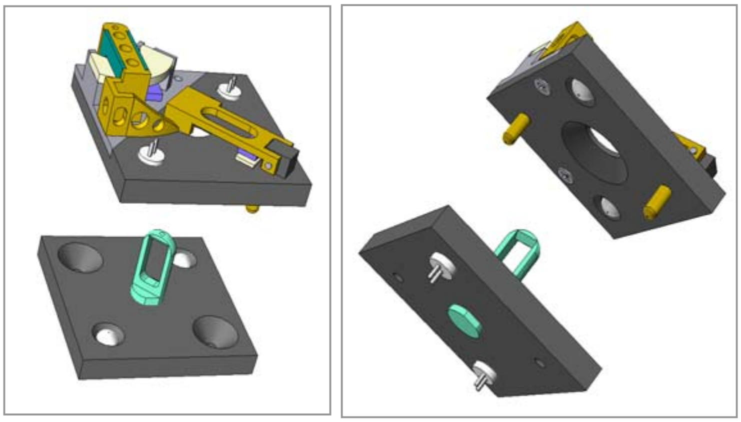
While this design is simple and occupies little space, it has certain limitations which have frequently rendered some rather sophisticated docking algorithms ineffective. In summary, the limitations of the design stem from these facts: a) engagement of the blade in the pin groves requires near-perfect alignment of the mating modules, and a strong and hence power-hungry SMA wire is needed to disengage the blade when the joint is under moderately heavy pulling or tilting force; and b) stronger SMA wires naturally require stronger retraction springs, which in turn impose the requirement for a powerful entrance push by the conical head of the pins to push back the blade upon docking. Experiencing these complications led us to the design and implementation of CAST.

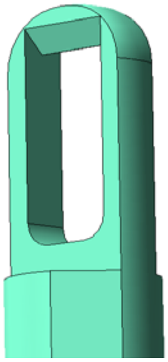
4. THE CAST DOCKING SYSTEM

CAST has been designed with the limitations of metamorphic robots in mind. These are the inherent cumulative positioning error, inaccuracy of sensory information, motion control limitations, limited power, and limited energy storage in robot modules. CAST effectively uses to its advantage both deliberate and random movements (the latter resulting from unaccounted servo responses, backlashes, plays, and possible material flexibilities) of modules upon docking and undocking. As shown in Figure 3, a CAST docking system, is made out of a male and a female docking module, each with a 25x25 mm square mating base made out of a hard polymer material (black delrin). Each module has an IR emitter and detector diagonally positioned on two corners of the square base plates.

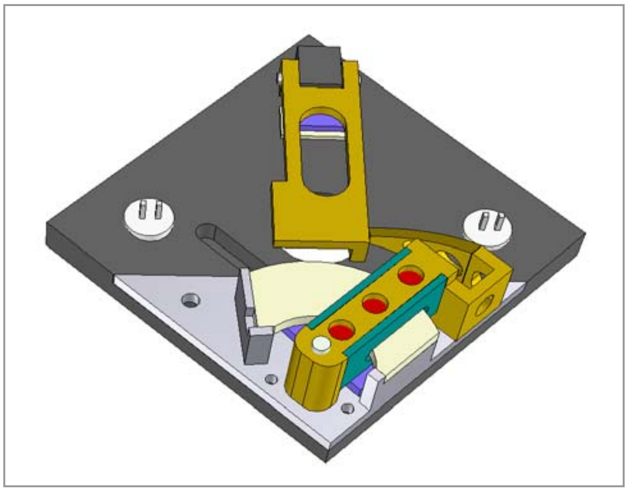
The male module includes a 5mm diameter pin with a round head that extends out from the center of the mating face of the module. The female module has a conical opening in its center to receive the pin. The round head of the pin and conical surface of the opening provide for self-alignment under a considerable lateral positioning error (about ± 7 mm). There are two smaller pins with round head diagonally positioned on the face of the female module. These pins enter two conical holes similarly positioned on the mating face of the male module. These pins provide for perfect mating while allowing rotational offset of about ± 30 degrees. CAST allows a directional offset of about ± 45 degrees. The whole docking module weighs less than 60 grams but has a holding force of over 10 kg.

The center pin of the male module (Figure 4) is shaped to a flat form toward the tip. The flat sides are in a 45 degree position with respect to the side of the square module body. A slot is machines on the flat part of the pin. This slot is 3.5 mm wide and 6 mm long. On the small inner side of the slot toward the pin, a sharp 45 degree edge is created. The pin is made out of stainless steel.





On the face opposite to the mating face of the female module, there is a latch that in its resting position covers the center opening of the module. This latch swivels around a hinge in one end and is always pulled to its resting position by the force of a small permanent magnet which is attached under it. In its resting position, the latch stops the rotational movement of a sloped blade installed on the same side of the female module (see Figure 5). The sloped blade is made out of brass and is attached to a pivoting arm. The pivoting arm holding the blade is also made of brass and is charged by the force of a small spring (or a thin elastic string – the type usually woven in the fabric of men's stockings) such



that it normally pulls the blade over the opening in the center of the female module. The maximum tension of the elastic element when the blade is pushed back to its extreme open position is roughly 10 grams. This elastic element is not shown in the CAD models but may be seen on the actual hardware picture in Figure 8. The view of the blade (from the direction of the normal to the mating face) is a section of a hollow cylinder. The pivoting point axis of the blade is a shaft that is located on this cylinder axis. As such, in its swiveling motion, all sections of the blade always pass through the center of the conical opening in the center of the female module. The pivoting arm of the blade is also equipped with an especially designed electric motor which is capable of overcoming the tension of the elastic element and bringing the blade back to its charged position. We will further describe this motor and its action when we present the undocking process. Following are the principles of operation of CAST for docking and undocking:

4.1 Docking

Upon docking, the tip of the pin on the male module enters the conical opening of the female module. As soon as the tip of the pin emerges from the opposite side of the mating face of the female module, the latch is pushed away by the tip of the pin in the direction of pin entrance. At this point the blade is released and by the force of the elastic element it attempts to enter the slot on the male module pin. The entrance of the blade in the pin slot locks the male module and from this point on any deliberate or random movement (as long as it has a vector component in the direction of docking), regardless of how small, pulls the male module toward the female counterpart with no possibility for retraction. In other words, the male module gets hooked and cannot get away unless an undocking command is issued to pull the blade back and out of the pin slot. Note that the sharp and hard (stainless steel) inner edge of the pin slot makes microscopic penetration in the soft brass of which the blade material is made. This prevents any slippage that could push the blade out of the pin slot due to angular force on the sloped edge of the blade. Furthermore, the pivoting arm holding the blade can move freely up and down the pivoting shaft for a small magnitude. In its lowest position, the bottom of the blade comes in contact with the surface of the female module polymer base. This contact adds significantly to a friction which further prevents the blade from moving back, even if there is a slippage of the pin over the blade. To further reduce the slippage possibility, the top edge of the blade may be roughened to provide for better locking of the sharp inner edge of the male pin.

Our experience has shown that once the hooking action is initiated the transition to near perfect and precise docking takes place very fast and with relative ease. In fact, rather than planning and executing calculated moves, we have coded an algorithm that simply shakes the modules in random patterns of motion. Perfect docking is then accomplished, usually in a couple of seconds. Note that in the final docking position the blade enters the pin slot all the way. At the upper end of the blade slope, there is a small flat area upon which the inner sharp edge of the mail pin rests in the final docking position (see Figure 6). The clearance of the flat surface with the tip of the sharp edge of the pin, when the two modules are manually pushed toward each other could be very small (e.g., 0.1 mm or less)[1]. A complete docking is signaled by the sensory data when a known maximum IR intensity is detected. The holding force of our CAST modules is in excess of 10 kg. Given the small size and light weight of the modules, this holding force is far above what is needed to link and operate many self-reconfigurable robot modules.

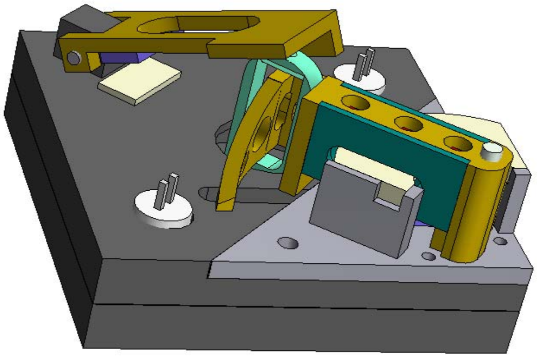


Figure 6. CAST in fully engaged mode

A design detail should be pointed out which concerns the inception of the hooking process. As the blade is released upon the pin entrance, the tip of the blade could collide with the solid tip of the male module pin instead of entering the pin slot. If in such a case the pin retracts outward the blade will be released and will rotate all the way to its locking position, thereby closing the entrance hole. The remedy in such a situation is a quick activation of the motor which would retract the blade and put it in its charged position. However, this would require a more elaborate sensing to signal that blade has locked without the pin having entered the female module. This possibility has been eliminated in our design by maintaining a clearance between the latch surface facing the male pin and the base surface of the female module (opposite to the mating surface). This clearance equals the distance between the inner sharp edge of the male blade (inside the pin slot toward the tip) to the tip of the pin. Consequently,

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[1] In a future article we will present an extension of this basic design which allows for zero clearance and a perfectly tight fit

the pin can release the latch only when its solid tip clears from the front of the tip of the locking blade. The blade always enters the pin slot and never collides with the solid tip of the pin. Furthermore, the size of the conical hole, diameter of the male pin, the width of the slot, and the width of the blade are designed such that the blade never collides with the sides of the pin slot. Any such collision could result in an unsuccessful hooking which only releases the latch and puts the blade in a locking position. As explained before, such a position will not allow the male module pin enter, because the conical hole would be blocked by the blade.

4.2 Undocking

The undocking action starts with first activating the electric motor in the female module. This motor can overcome the spring pull force and rapidly return the blade to its unlocking position and thereby releasing the pin of the male module. The motor, however, can act effectively, only when momentarily (a few milliseconds) the modules are pushed toward each other such that the sharp inner edge of the pin momentarily separates from the blade. Even a very small separation gap of a few microns happening in a few milliseconds could result in the release and retraction of the blade by the biased force exerted by the electric motor. When the blade retracts, the pin is released and the modules can undock. The motor is kept charged until the sensory data indicates that the modules are sufficiently apart from one another. At this point the charge to the motor is switched off but the blade is stopped by the latch which has pushed itself to its resting position under the force of its permanent magnet. Note that a magnet is used instead of a spring because unlike a spring, a magnet exerts its maximum force when it is in close proximity of the element which it attracts (in this case a small and thin metal plate glued to the female module polymer base surface directly under the latch). The maximum pulling force is needed when the latch is in its resting position so that sudden and jerky robot motions do not move the latch and unwontedly release the blade. Also, weak attraction force for the latch is needed when the latch released the blade and rests on it, in the unlikely event where the male module pin pushes and releases the latch but a successful hooking does not take place. In such a case the retraction force of the latch should not obstruct the retraction of the blade when the motor is energized.

Note that in this configuration the CAST docking system is passive during docking, and only momentarily consumes a small amount of electric power during undocking.

5. CAST MOTOR

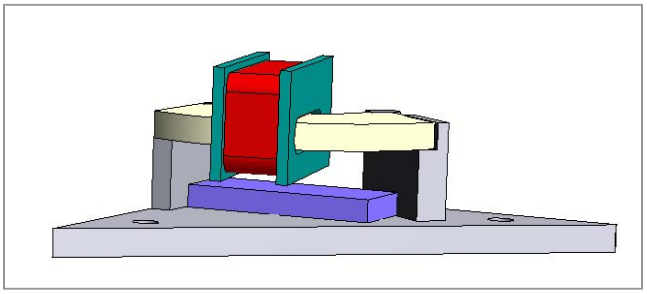
We used electric motor, rather than SMA wire for actuation needs of CAST because of the following reasons:

i) The reaction speed of SMA is far less than an electric motor. SMA wires are also slow to stretch under spring force when they are de-energized. This is especially limiting upon docking when the latch releases the blade and the blade has to quickly enter the slot of the male module pin.

ii) If SMA wire is prevented from retraction upon activation its internal structure breaks down and it permanently loses its actuation property. Electric motors, however, may be safely stalled under load. This feature is important in CAST because upon undocking the locking blade may be momentarily prevented from retraction by the mail module pin which may stay engaged with the blade for unpredictable durations. A simple and reliable design based on SMA wire is not possible for such cases.

iii) SMA wire consumes considerably more energy than a motion device based on electric motor with equal payload. The slow reaction of SMA wires also imposes excessive power usage during the non-productive warm-up period.

The CAST motor (shown in Figure 7) is especially designed to perform a partial revolution at a relatively constant force along the range of its motion. This has been accomplished by the use of a 1.8 mm thick flat rare earth magnet block with the magnetic polarities on its largest surfaces. The magnet is placed on a base metal made of pure iron. Two vertical bases made of the same metal bring the polarity on the surface of the lower surface of the magnet (i.e., the surface attached to the iron base) to a top flat iron piece which is shaped as a section of a flat ring with its center at the pivot axis of the blade. This arrangement creates a strong magnetic flux between the base iron and the top piece which bridges the two vertical bases. The bridge piece passes through a coil made of 44 gauge coil copper wire. The current direction in those coil wires that are sandwiched between the two magnetic polarities at the lower section of the coil is perpendicular to the flux vector. The coil is hence pushed side ways as DC power is applied to it. The direction of the move may be changed by reversing the DC polarity (note that such a change of polarity is not needed in CAST). The coil wire resistance is about 150 Ohms. The motor operates at 3 Volts, hence it draws a 200 MA current. The motor power consumption, therefore, is only 0.6 watts. Note again that



the motor is only energized momentarily upon undocking, which in our experiments has not taken more than 2 seconds. This may make CAST the most efficient and highly compliant docking system in existence today. The power consumption of CAST compared to SMA based systems (used in most current docking systems) is very negligible.

Because of its limited range of motion, the power to the CAST motor need not be transferred through brushes. Simple connections through flexible wires (earphone wire strands which are made by very thin ribbon metal wire wound around thin synthetic fibers) can transfer the electric power and operate without breaking for thousands of operations.

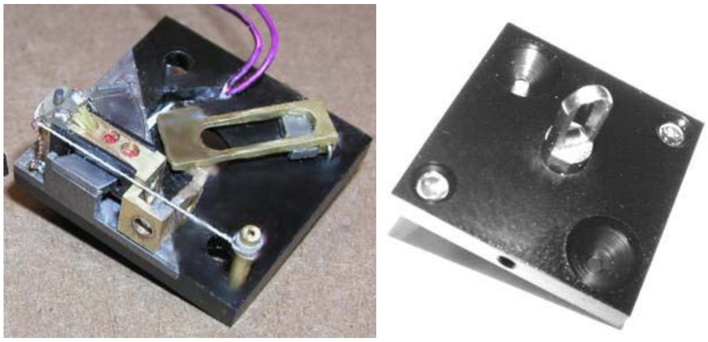


Figure 8. CAST actual hardware

6. CONCLUSION

CAST is a highly-Compliant and self-tightening docking system in which deliberate moves, vibrations, or other small disturbances in the system is sufficient for fast, precise and tight docking. Besides its applicability in metamorphic robotic systems, the module is applicable in a large number of scenarios where precise approach to grasping is not possible but precise grasping is required. Automated tool change in manufacturing and assembly, docking in space, and picking part containers with random orientation are some other potential application areas. The male module in CAST is very simple and hence it may be made very inexpensively and attached to a variety of target objects to be grasped and released by a robotic arm which is equipped with the female CAST module.

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