Self-reconfigurable Modular Connection Systems

Nick Eckenstein[1], Tarik Tosun [2], and Mark Yim[3]

Abstract— **All self-reconfiguring robot systems have one thing in common, the ability dock and undock with other modules. This dock or undock subsystem requires some kind of reversible bonding mechanism. In addition, most self-reconfigurable systems rely on a variety of alignment mechanisms to ensure docking occurs correctly. This paper briefly surveys two aspects of self-reconfigurable robots, the area of acceptance, and of latching. Maximizing the area of acceptance enables the joining of two docking faces with a minimum of precision. Latching is the bonding mechanism by which two docking faces mate.**

I. INTRODUCTION

In 1993–1994, Satoshi Murata [1], Greg Chirikjian [2] and Mark Yim [3] had separately developed similar self-reconfigurable modular robot ideas, showing robots that promised to be versatile, low cost and robust. These systems were made up of one type of module (homogeneous), with varying capabilities that tended to scale with the number of modules. One characteristic of modular self-reconfigurable robots is that they need intense hardware development. There are dozens of groups who have constructed many versions of reconfigurable robots [4], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], [21], with many approaches for programming them [22], [23], [24], [25], [26], [27], [28], [29], [30], [31], [32], [33], [34], [35], [36], [37], [38], [39]. Over 800 papers and a book [40] have been written including a survey led by PI Yim [41].

There are three categories of reconfiguring systems: chain, lattice, and mobile [42]. The chain systems tend to be the most capable to do useful tasks, as they can form articulated limbs. The lattice systems tend to be the best at reconfiguration. The mobile systems have modules that individually maneuver on terrain. Of the systems that have been implemented to date, some that have been shown to be most capable (judging by number of demonstrations) are the hybrid chain-lattice systems: Superbot [43], MTRAN III [44]) and CKbot [45]). Another recent interesting addition to the community is iMobot [46] which is a hybrid chain-lattice-mobile system. Each module in this system has the ability to travel on flat ground independently and can dock and undock (though this last functionality has yet to be demonstrated autonomously).

These systems have exhibited a wide variety of locomotion and manipulation including: legged walking with two, three, four, six, and fourteen legs; riding a tricycle; rolling like a tread; slithering like a slinky, rectilinear undulation, concertina, sidewinding and other different snake gaits; manipulation of large objects with multiple arms/fingers; manipulation of small objects; climbing stairs, poles, in pipes; self-reconfiguration between dozens of shapes and many others.

The one subsystem that is common in all of these systems is a docking / undocking system. The docking process is divided into two parts: *alignment*, in which the modules obtain a sufficiently accurate relative position, and *latching* where the physical connection between the modules is made or forces put in place which maintain the alignment.

II. DOCKING FACES

In general, docking between two modules occurs at special docking faces on a module also called a connector. Faces can be gendered or ungendered. Gendered faces have male and female features which must be matched, and thus must be carefully controlled to ensure connections are formed from one of each face. Ungendered faces do not have this restriction. Hermaphroditic faces have both male and female features on each face.

Another requirement for reconfigurable connectors is the ability to undock successfully as well as dock. If mechanical connection is being used, either the docking or undocking requires some actuation capabilities. One or the other of these processes can proceed passively but in order for the connection to be stable under all possible force/torque conditions, there needs to be an active state change. Historically this has been accomplished by SMA or small motors[47].

We introduced the concept of **Area of Acceptance** (AA) in the previous work on the 2D X-Face [48]. Area of acceptance is defined as 'the range of possible starting conditions for which mating will be successful'[48]. More generally, given some approach condition and pair of docking objects, the AA is the set of all initial poses (relative to each other) that result in intimate alignment of the two parts.

Few connector designs of this type have been evaluated extensively for acceptance range. Nilsson [49] mathematically determined a bound on self-alignable offsets for 2D mechanical connectors with the restriction that they be definable as a function. He applied this notion of self-alignable offsets to his characterization of the DRAGON connector[50] and determined its maximum offsets individually in all relevant degrees of freedom (DOF). The X-Claw[51] was an active connector which had its error tolerance characterized - in (x,y,z) in combination, and (roll, pitch, yaw) individually.By utilizing multiple layers, the 2D X-Face accomplished a

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[1]Nick Eckenstein `neck@seas.upenn.edu`

[1]Tarik Tosun `tarikt@seas.upenn.edu`

[1]Mark Yim `yim@seas.upenn.edu` are all with the Department of Mechanical Engineering and Applied Mechanics, University of Pennsylvania, Philadelphia, PA 19104, USA

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200% increase in positional offset AA for 2D connectors over the bound on ungendered 2D connectors determined by Nilsson. Significant increases in combined position-orientation AA were also shown.

A. Area of Acceptance

We can classify AA into different types with respect to the DOFs of one docking element relative to the other. The DOF are either *constrained, unconstrained*, or the *approach* DOF. When two docking faces are brought together, typically some motion of the faces relative to each other are free to comply so that sliding contact between the two faces in those complying directions bring the faces into alignment. Of course the faces need to be designed so that this happens. In the most general 3D case, one face has six DOFs relative to the other ($SE(3)$) with one DOF encompassing the approach direction. While this approach DOF is typically considered to be a positional DOF, it could be any that lead to lower kinematic pair relationships including screws. The other five DOFs are unconstrained. Being constrained in this case means that those DOFs are assumed to always be aligned.

In some cases, where the faces have a symmetry (e.g. a round peg, in round hole) one or more DOF is in a "don't care" state. Whereas the end mating condition in all other cases has the state of all DOFs defined, this one has the other symmetric DOFs make no functional difference and so do not need to match to satisfactorily mate.

A wide variety of specialized connectors for modular robots, typically magnetic, electrostatic or mechanical[52]. The hermaphroditic DRAGON Connector has a high area of acceptance classified in several individual dimensions of offset (linear and angular), and contains a heavy-duty passive latching mechanism to withstand high loads[50]. The SINGO Connector is a hermaphroditic connector with an actively driven spiral gear mechanism that ultimately results in high error correctability over certain directions of offset[53]. The hermaphroditic X-Claw connector[51] uses an active gripper and mechanical self-alignment features to ensure a high area of acceptance as well as 4 possible attachment orientations between two given faces. Unfortunately the X-Claw also suffered from a relatively loose grip and weak component strength.

Docking connectors have also been used and studied in aerospace applications (i.e. rendezvous and docking systems), however the essential requirements and mission can be very different and thus result in different systems. Space docking mechanism requirements include robustness, impact absorption, and reversibility[54]. Modular robots connector design on the other hand prioritizes tolerance to alignment errors (area of acceptance), small profile size, and low power and actuation[40]. These elements lead us to study passive mechanical self-aligning mechanisms with high area of acceptance as the basic shape for our designs.

III. MODULAR ROBOT LATCHING SYSTEMS

A wide variety of connectors for hybrid modular robots can be found in the literature. Some systems that use magnets include MTRAN II [6] and the Telecubes system [14]. Both use permanent magnets for latching, and disconnect them using shape-memory alloy (SMA) actuators. The disadvantage of SMA is its slow response time, as it can take minutes to cool after heating and are notoriously energy inefficient. SMORES-EP uses electro-permament magnets that are is able to switch the state of its EP magnets in milliseconds.

Electro-permanent magnets are bistable magnetic connectors that require power only when connecting and disconnecting. They have many advantages: high speed, high strength, low power consumption, and the ability to inductively transmit communication signals between connected magnets.

Telecubes and MTRAN II both exert connector forces of about 25N per magnet, about the same as SMORES-EP. Structural hook-type connectors are popular for hybrid self-reconfigurable robots. Examples include the ATRON and MTRAN III robots [55], [43], [44]. The advantage of these connectors is high strength: ATRON can support up to 800N. Compared to magnets, they sacrifice versatility and require large amount of space. The majority of volume within each module of the ATRON was consumed by the connection mechanism. They also tend to be mechanically complex, with many moving parts that can break or wear over time.

The SINGO connector, developed for the Superbot robot, is more versatile [56]. It is hermaphroditic, and capable of disconnection even when one module is unresponsive, allowing for self-repair. However, it is mechanically complex, and sacrifices some strength for versatility.

IV. CONCLUSION

We survey a wide variety of connectors for self-reconfiguring systems. In particular we focus on area of acceptance which tends to yield more robust self-reconfiguration to imprecision and with bonding methods. One of the more recent promising bonding methods is the electro-permanent magnet connectors.

REFERENCES

[1] S. Murata, H. Kurokawa, and S. Kokaji, "Self-assembling machine," in *Proc. IEEE Int. Conf. on Robotics and Automation*, San Diego, California, May 1994.

[2] G. S. Chirikjian, "Kinematics of a metamorphic robotic system," in *Proc. of the IEEE Intl. Conf. on Robotics and Automation*, San Diego, Ca, May 1994, pp. 449–455.

[3] M. Yim, "A reconfigurable modular robot with many modes of locomotion," in *Proc. of the JSME Int. Conf. on Advanced Mechatronics*, Tokyo, Japan, 1993, pp. 283–288.

[4] T. Fukuda and Y. Kawauchi, "Cellular robotic system (cebot) as one of the realization ofself-organizing intelligent universal manipulator," in *Proc. IEEE Intl. Conf. on Robotics and Automation*, Cincinnati, OH, USA, May 1990, pp. 662–667.

[5] D. Rus and M. Vona, "Self-reconfiguration planning with compressible unit modules," in *Proc. of the IEEE Intl. Conf. on Robotics and Automation*, Detroit, 1999.

[6] S. Murata, E. Yoshida, K. Tomita, H. Kurokawa, A. Kamimura, and S. Kokaji, "Hardware design of modular robotic system," in *Proc. IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, Takamatsu, Japan, October 2000.

[7] K. Kotay and D. Rus, "Self-reconfigurable robots for navigation and manipulation," in *Proceedings of the 1995 IEEE/RSJ International Conference on Intelligent Robots and Systems*, Grenoble, France, September 1997.

[8] C. Ünsal, H. Kýlýççöte, and P. K. Khosla, "I(ces)-cubes: A modular self-reconfigurable bipartite robotic system," in *Proc. of SPIE, Sensor Fusion and Decentralized Control in Robotic Systems II*, 1999, pp. 258–269.

[9] A. Castano, W. M. Shen, and P. Will, "Conro: Towards deployable robots with inter-robots metamorphic capabilities," *Autonomous Robots*, vol. 8(3), pp. 309–324, 2000.

[10] C. J. J. Paredis, H. B. Brown, and P. K. Khosla, "A rapidly deployable manipulator system," in *Proc. IEEE Int. Conf. Robotics and Automation*, Minneapolis, MN, April 1996.

[11] W. H. Lee and A. C. Sanderson, "Dynamic analysis and distributed control of the tetrobot modular reconfigurable robotic system," *Autonomous Robots*, vol. 10, no. 1, pp. 67–82, January 2001.

[12] H. C. H. Chiu, M. Rubenstein, and W.-M. Shen, "Multifunctional superbot with rolling track configuration," in *IEEE/RSJ Intl. Conf. on Intelligent Robots and Systems*, San Diego, CA, November 2007.

[13] E. Tuci, R. Gross, V. Trianni, F. Mondada, M. Bonani, and M. Dorigo, "Cooperation through self-assembly in multi-robot systems," *ACM Transactions on Autonomous and Adaptive Systems (TAAS)*, vol. 1, no. 2, pp. 115–150, 2006.

[14] J. Suh, S. Homans, and M. Yim, "Telecubes: mechanical design of a module for self-reconfigurable robotics," in *Robotics and Automation, 2002. Proceedings. ICRA'02. IEEE International Conference on*, vol. 4, 2002.

[15] M. Jorgensen, E. Ostergaard, and H. Lund, "Modular atron: modules for a self-reconfigurable robot," in *Proc. of 2004 IEEE/RSJ Intl. Conf. on Intelligent Robots an d Systems (IROS2004)*, October 2004, pp. 2068–2073.

[16] M. Hafez, M. Lichter, and S. Dubowsky, "Optimized binary modular reconfigurable robotic devices," *Mechatronics, IEEE/ASME Transactions on*, vol. 8, no. 1, pp. 18–25, 2003.

[17] P. White, V. Zykov, J. Bongard, and H. Lipson, "Three dimensional stochastic reconfiguration of modular robots," in *Proceedings of Robotics Science and Systems*, 2005, pp. 161–168.

[18] B. Kirby, J. Campbell, B. Aksak, P. Pillai, J. Hoburg, T. Mowry, and S. Goldstein, "Catoms: Moving Robots without Moving Parts," in *PROCEEDINGS OF THE NATIONAL CONFERENCE ON ARTIFICIAL INTELLIGENCE*. Menlo Park, CA; Cambridge, MA; London; AAAI Press; MIT Press; 1999, 2005, p. 1730.

[19] S. Goldstein, J. Campbell, and T. Mowry, "Programmable Matter," *COMPUTER*, pp. 99–101, 2005.

[20] A. Goldenberg, N. Kircanski, P. Kuzan, J. Wiercienski, R. Hui, and C. Zhou, "Modular, expandable and reconfigurable robot," Jun. 4 1996, uS Patent 5,523,662.

[21] H. Lipson and J. Pollack, "Towards continuously reconfigurable self-designing robotics," in *Robotics and Automation, 2000. Proceedings. ICRA'00. IEEE International Conference on*, vol. 2, 2000.

[22] J. Walter, E. M. Tsai, and N. Amato, "Choosing good paths for fast distributed reconfiguration of hexagonal metamorphic robots," in *Proc. of the IEEE Int. Conf. on Robotics and Automation*, 2002.

[23] K. Støy, W. M. Shen, and P. Will, "Global locomotion from local interaction in self-reconfigurable robots," in *Proc. of the 7th Intl. Conf. on intelligent autonomous systems (IAS-7)*, Marina del Rey, California, March 25-27 2002.

[24] P. W. B. Salemi, W.M. Shen, "Hormone-controlled metamorphic robots," in *Proc. of the IEEE Intl. Conf. on Robotics and Automation*, 2001, pp. 4194–4199.

[25] A. Kamimura, S. Murata, E. Yoshida, H. Kurokawa, K. Tomita, and S. Kokaji, "Self-reconfigurable modular robot - experiments on reconfiguration and locomotion," in *Proc. of 2001 IEEE/RSJ Intl. Conf. on Intelligent Robots and Systems (IROS200)*, Maui, Hawaii, October 2001, pp. 606–612.

[26] R. Fitch, D. Rus, and M. Vona, "Basis for self-repair robots using self-reconfiguring crystal modules," in *Proc. IEEE Int. Autonomous Systems 6*, 2000, pp. 903–910.

[27] I. M. Chen and G. Yang, "Automatic generation of dynamics for modular robots with hybrid geometry," in *Proc. of the IEEE Intl. Conf. on Robotics and Automation*, Albuquerque, New Mexico, April 1997, pp. 2288–93.

[28] I. M. Chen and J. Burdick, "Enumerating the non-isomorphic assembly configurations of a modular robotic system," *Intl. Journal of Robotics Research*, vol. 17(7), pp. 702–719, 1996.

[29] G. S. Chirikjian, A. Pamecha, and I. Ebert-Uphoff, "Evaluating efficiency of self-reconfiguration in a class of modular robots," *Journal of Robotic Systems*, vol. 13(5), pp. 317–338, May 1996.

[30] A. Castano, W. M. Shen, and P. Will, "Conro: Towards deployable robots with inter-robot metamorphic capabilities," *Autonomous Robots Journal*, vol. 8(3), pp. 309–324, July 2000.

[31] F. B. III and E. Rieffel, "Design of decentralized controllers for self-reconfigurable modular robots using genetic programming," in *Proc. of the 2nd NASA/DoD Workshop on Evolvable Hardware (EH-2000)*, 2000.

[32] Z. Butler, R. Fitch, and D. Rus, "Distributed control for unit-compressible robots: goal-recognition, locomotion, and splitting," *IEEE/ASME Transactions on Mechatronics*, vol. 7, no. 4, pp. 418–430, December 2002.

[33] J. E. Walter, J. L. Welch, and N. M. Amato, "Distributed reconfiguration of metamorphic robot chains," *Distributed Computing*, vol. 17, no. 2, pp. 171–189, August 2004.

[34] Y. Zhang, M. Fromherz, L. Crawford, and Y. Shang, "A general constraint-based control framework with examples in modular self-reconfigurable robots," *Proceedings of the 1995 IEEE/RSJ International Conference on Intelligent Robots and Systems*, vol. 3, pp. 2163–2168, 2002.

[35] A. Castano and P. Will, "Representing and discovering the configuration of conro robots," in *Proc. of the IEEE Intl. Conf. on Robotics and Automation*, Seoul, Korea, May 2001, pp. 3503–09.

[36] H. Bojinov, A. Casal, and T. Hogg, "Emergent structures in modular self-reconfigurable robots," in *Robotics and Automation, 2000. Proceedings. ICRA'00. IEEE International Conference on*, vol. 2, 2000.

[37] P. Pirjanian, C. Leger, E. Mumm, B. Kennedy, M. Garrett, H. Aghazarian, S. Farritor, and P. Schenker, "Distributed control for a modular, reconfigurable cliff robot," in *Robotics and Automation, 2002. Proceedings. ICRA'02. IEEE International Conference on*, vol. 4, 2002.

[38] K. Prevas, C. Unsal, M. Efe, and P. Khosla, "A hierarchical motion planning strategy for a uniform self-reconfigurable modular robotic system," in *Robotics and Automation, 2002. Proceedings. ICRA'02. IEEE International Conference on*, vol. 1, 2002.

[39] W. Melek and A. Goldenberg, "Neurofuzzy control of modular and reconfigurable robots," *Mechatronics, IEEE/ASME Transactions on*, vol. 8, no. 3, pp. 381–389, 2003.

[40] K. Støy, *An Introduction to Self-Recongurable Robots*. Boston, MA: MIT Press, 2009, to appear.

[41] M. Yim, W. Shen, B. Salemi, D. Rus, M. Moll, H. Lipson, E. Klavins, and G. Chirikjian, "Self-Reconfigurable Robot Systems," *IEEE Robotics & Automation Magazine*, p. 44, 2007.

[42] M. Yim, D. Duff, and K. Roufas, "PolyBot: a modular reconfigurable robot," in *Robotics and Automation, 2000. Proceedings. ICRA '00. IEEE International Conference on*, vol. 1, 2000, pp. 514 –520 vol.1.

[43] B. Salemi, M. Moll, and W.-M. Shen, "SUPERBOT: A Deployable, Multi-Functional, and Modular Self-Reconfigurable Robotic System," in *Intelligent Robots and Systems, 2006 IEEE/RSJ International Conference on*, Oct. 2006, pp. 3636 –3641.

[44] S. Murata, K. Kakomura, and H. Kurokawa, "Toward a scalable modular robotic system," *Robotics Automation Magazine, IEEE*, vol. 14, no. 4, pp. 56 –63, Dec. 2007.

[45] M. Yim, B. Shirmohammadi, J. Sastra, M. Park, M. Dugan, and C. Taylor, "Towards robotic self-reassembly after explosion," in *Intelligent Robots and Systems, 2007. IROS 2007. IEEE/RSJ International Conference on*, 29 2007-Nov. 2 2007, pp. 2767 –2772.

[46] H. C. G. Ryland, "Design of iMobot, an Intelligent Reconfigurable Mobile Robot with Novel Locomotion," May 2010.

[47] 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. [Online]. Available: http://ijr.sagepub.com/content/27/3-4/373.abstract

[48] N. Eckenstein and M. Yim, "The x-face: An improved planar passive mechanical connector for modular self-reconfigurable robots," in *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, 2012, pp. 3073–3078.

[49] M. Nilsson, "Symmetric docking in 2d: A bound on self-alignable offsets," in *IASTED '99: Robotics and Automation*, Oct. 1999.

[50] ——, "Heavy-duty connectors for self-reconfiguring robots," in *Robotics and Automation, 2002. Proceedings. ICRA '02. IEEE International Conference on*, vol. 4, 2002, pp. 4071 – 4076 vol.4.

[51] J. J. Cong and R. Fitch, "The x-claw self-aligning connector for self-reconfiguring modular robots," in *IROS '11: Proceedings of the Workshop on Reconfigurable Modular Robotics: Challenges of Mechatronic and Bio-Chemo-Hybrid Systems*, 2011.

[52] N. Eckenstein and M. Yim, “Area of acceptance for 3d self-aligning robotic connectors: concepts, metrics, and designs,” in *2014 IEEE International Conference on Robotics and Automation (ICRA)*. IEEE, 2014, pp. 1227–1233.

[53] 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 *IEEE International Conference on Robotics and Automation*, 2009, pp. 4253–4258.

[54] F. Gampe, K. Priesett, and R. Bentall, “A modular docking mechanism for in-orbit assembly and spacecraft servicing,” in *19th Aerospace Mechanisms Symposium 1985*, 1985, pp. 59–74.

[55] M. Jorgensen, E. Ostergaard, and H. Lund, “Modular ATRON: modules for a self-reconfigurable robot,” in *Intelligent Robots and Systems, 2004. (IROS 2004). Proceedings. 2004 IEEE/RSJ International Conference on*, vol. 2, Sept. - Oct. 2004, pp. 2068 – 2073 vol.2.

[56] 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 *Robotics and Automation, 2009. ICRA ’09. IEEE International Conference on*, May 2009, pp. 4253 –4258.