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DEVELOPMENT OF A NOVEL COUPLING MECHANISM FOR MODULAR SELF-RECONFIGURABLE MOBILE ROBOTS

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ABSTRACT

This paper presents the development of a novel coupling mechanism for modular self-reconfigurable mobile robots. Modular self-reconfigurable mobile robotic systems consist of a large number of self-sufficient modules that can transform into various configurations. One of the most challenging tasks in this field is designing a reliable and flexible coupling mechanism that physically connects modules to form larger and more articulated structures to scale up locomotion and manipulation functions. In this research we propose GHEFT: a Genderless, High strength, Efficient, Fail-safe, and high misalignment Tolerant coupling mechanism that aids the process of self-reconfiguration, and self-repair. Many existing coupling mechanisms fail to possess these crucial design features. The proposed mechanism ensures an efficient and high strength connection due to non-back drivable actuation and specially designed clamping profiles that enables modules to tolerate large misalignments and engage/disengage without gender restrictions in the presence of one-sided malfunction; thus, increasing both the versatility and robustness of the entire robotic system. In this paper, misalignment analysis is performed to formulate simple relations based on clamping profile design parameters to achieve specific misalignment tolerances based on application requirements. These formulations are used to compute maximum misalignment tolerances. Dynamic simulations are then performed to determine maximum misalignment tolerance capabilities and verify computed tolerances.

INTRODUCTION

In recent years, researchers have gained inspiration from biological systems such as the subcellular structures called molecules that self-construct out of relatively simple building blocks, amino acids, and form complex structures called proteins [1]. This source of inspiration has motivated engineers to establish the field of modular self-reconfigurable mobile robotics. These robotic systems consist of a large number of self-sufficient modules capable of processing, sensing and actuation. Modules can self-reconfigure, a process in which discrete modules dock (connect) to each other without external commands [2], by interconnecting with neighboring modules via a coupling mechanism and change their structure to enable new functionalities and adapt to unknown tasks and environments. Figure 1 shows the self-reconfiguration concept of three STORM modules initially scattered about an area (Fig. 1A) then self-reconfiguring into a humanoid configuration to retrieve an item from an elevated height (Fig. 1B) [3].

The flexibility of modular self-reconfigurable robots has motivated researchers to develop numerous robotic systems [4-12]. These robotic systems provide three main advantages over conventional single structured robots: 1) Versatility due to their adaptive nature that enables interconnected modules to disassemble and reassemble into new configurations that are better adapted to tasks and environments. 2) Robustness due to exploiting redundancies within robotic structures and the capabilities of performing self-repair, a process in which a damaged module is autonomously replaced [13]. 3) Low production costs due to batch fabrication of homogeneous modules [14].

These advantages are desirable for applications where tasks and environments are not known a priori or when a volume and mass constraints are of significance. One such application can be an outer space mission where a relatively few number of modules occupying a small area can be stored on board a spacecraft and commanded to reconfigure into various structures to complete unknown tasks in unfamiliar environment. This concept may be extended further to applications such as undersea mining, search and rescue and battle field reconnaissance.

The field of modular self-reconfigurable mobile robotics [15] has evolved from a proof-of-concept to elaborate systems; however have yet to be practically demonstrated due to reconfiguration difficulties [16]. The main technical challenges hindering advancements in this field is the design of a coupling mechanism that efficiently connects/disconnects modules and permits the transfer of large mechanical forces and moments without imposing coupling constraints and degrading performance. The majority coupling mechanisms found in literature rely on gendered connectors that require double sided operation and continuous power consumption to establish and maintain a connection between adjacent modules. Therefore, the presence of a mechanical failure within a single mechanism will result in the failure of the entire robotic system due to the lost ability of disengagement; hindering self-repair. In addition, coupling mechanisms were not designed with the vision of connecting a large number of modules within a robotic structure, resulting in low strength mechanisms that are prone to failure when exposed to high loads. To this date, only two coupling mechanisms have addressed the issues of high rigidity and strength [17,18]. Few attempts have been made so far that demonstrate self-reconfiguration with results often requiring ideal laboratory conditions [19]. Self-reconfiguration has only been successfully demonstrated on flat surfaces due to coupling mechanisms low translational/angular misalignments tolerances.

The aim of this research is to develop a flexible and reliable coupling mechanism to aid the process of self-reconfiguration and self-repair to exploit the advantages of modular self-reconfigurable mobile robots. The GHEFT is the proposed mechanisms that is designed to offer an efficient, high strength and misalignment tolerant connection due to non-back drivable actuation and specially designed clamping profiles that enables both engagement/disengagement of modules without gender restrictions in the presence of one-sided malfunction; thus, increasing both the versatility and robustness of the entire robotic system.

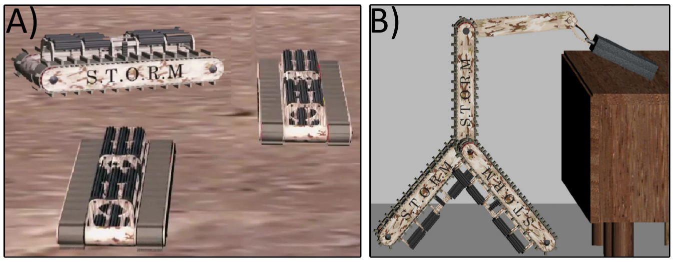

Figure 1. Concept of Self-reconfiguration of STORM. A) Initially scattered STORM modules about an area. B) Self-reconfigured humanoid configuration

This paper provides an overview of modular self-reconfigurable robots coupling mechanisms designs and discusses the necessary design requirements of a coupling mechanism based on optimal design features identified in the review. The detailed design of the GHEFT is then presented after which misalignment analysis is performed to formulate relations dependent on clamping profile design parameters to achieve specific misalignment tolerances. Dynamic simulations are conducted to demonstrate and determine maximum misalignment tolerances capabilities of the mechanism. Finally, concluding remarks and future work are discussed.

OVERVIEW OF COUPLING MECHANISM DESIGNS

Over the years, as the field of modular self-reconfigurable mobile robotics evolved into more elaborate systems so did the coupling mechanisms used to connect modules. This section reviews several state of the art coupling mechanisms in order to identify necessary design requirements.

CEBOT[7] and PolyBot [14], modular robots developed in the late 1980s and 1990s, utilize coupling mechanisms are similar in design. Both mechanisms rely on gendered male components, cone shaped ports or grooved pins, that are inserted into chambered holes on the opposing module and latched using a spring loaded rotating plate actuated by shape memory alloy (SMA). This form of actuation constantly consumes power to maintain a connection and provides low clamping forces; thus, creating difficulties in connecting a large number of modules within a robotic structure for a prolonged period of time. Chamfered holes and pins offer slight misalignment tolerances in the range of a few millimeters and degrees depending on the radius and chambers on the gendered connectors. These gendered connections also impose undesirable configuration constraints that are not fail-safe, the ability to engage or disengage a connection in the presence of one-sided failure, since the undocking procedures rely solely on the female coupling unit.

GENFA [20] and SINGO [21] were the first coupling mechanisms designed with genderless, fail-safe characteristics. GENFA utilizes a rotary disk that latches onto chamfered pins to establish connections between two modules. The chamfered pins offer 20 degrees of angular misalignment tolerance; however, can only tolerate 1-3 mm transnationally. SINGO consists of four jaws that slide on linear trails to connect with other modules. Its design is intolerant to angular misalignments and has low connection strength in terms of payload carrying capabilities and moment loading. Both mechanisms low angular or translational misalignment tolerances create difficulties in achieving self-reconfiguration.

Many other coupling mechanisms were proposed in literature; however critical design features limit overall performance of robotic system. For example, connections relying on permanent magnets [22-23] or electromagnetic forces [24-25] do provide low range translational and angular misalignment tolerances, in the order of a few millimeters and degrees; however, operate inefficiently due to constant power consumption, are low in connection strength and may lose connection unintentionally if one module malfunctions.

Coupling mechanisms utilizing physical latches and pins [26-33] are most often times gendered and not fail-safe; therefore, adding constraints to connections between two modules and preventing the ability of self-repair in the presence of malfunctioning components.

COUPLING MECHANISM DESIGN REQUIREMNTS

Coupling mechanisms are often considered the most crucial component of any modular self-reconfigurable mobile robot since flawed designs can severely limit the entire robotic systems performance. Nillson outlined basic guidelines on designing coupling mechanisms for modular systems [34]. In general, due to modules limited power supplies, a coupling mechanism should provide a power efficient mechanical connection between two modules, consume minimal energy once docked and prevent accidental unlatching. These three requirements can be achieved through the use of non-back-drivable clamping actuation. This type of actuation consumes power during the docking process; then, once a connection is established, power is no longer required and accidental unlatching is prevented due to single-directional flow of motion.

Transitioning from controlled laboratory conditions into the real world environments introduces difficulties in designing reliable coupling mechanisms. Prior to initiating the self-reconfiguration process, modules must precisely align themselves with respect to a docking target to ensure the engagement of their respective coupling mechanisms. However, due to un-modeled terrain, propagated sensor error and control system error, both translational and angular misalignments must be tolerated through the mechanism design. Therefore, it is necessary for a coupling mechanism to tolerate large misalignments to ensure successful docking.

As robotic configurations grow during the self-reconfiguration process so do the mechanical loadings acting on the structural components of the mechanisms. Therefore, it is necessary that the design and construction of the coupling mechanism be high in strength and rigidity so as not to fail during operation. However, mechanical failure is inevitable. A robotic system must have the means of performing self-repair to replace malfunctioning modules. To achieve this, coupling mechanisms must poses fail-safe criteria.

Another important consideration is the flexibility of the coupling mechanism. Modular self-reconfigurable mobile robots are usually homogenous in nature to exploit low cost batch fabrication. The performance of these robots must not be limited in achievable configurations due to a gendered coupling mechanism that is, requiring male and female connectors. A genderless coupling mechanism will greatly facilitate the vision of versatility because it allows any two components to connect without gender restrictions imposed by their connectors.

MECHANICAL DESIGN OF GHEFT

The basic principle of a coupling mechanism is to constrain all translational and rotational degrees of freedom (DOF) between two neighboring modules. The GHEFT achieves this through its specially designed symmetric, H-grooved clamping profiles that translate about open slots within a sliding plate as depicted in Fig. 2. The clamping profiles act as followers when a high torque servomotor rotates a constant lead cam located behind the sliding plate. Depending on the direction of rotation, the clamping profiles either move outward or inward to meet at the center. Figure 3 provides an inside view of the GHEFT assembly showing both the cam and its servo motor. A sliding plate ensures pure translational motion of the clamping profiles. The cam/follower system provides efficient, non-back drivable actuation and a reliable connection once the coupling mechanism is engaged since any attempt to translate the follower will not rotate the cam and cause the accidental unlatching.

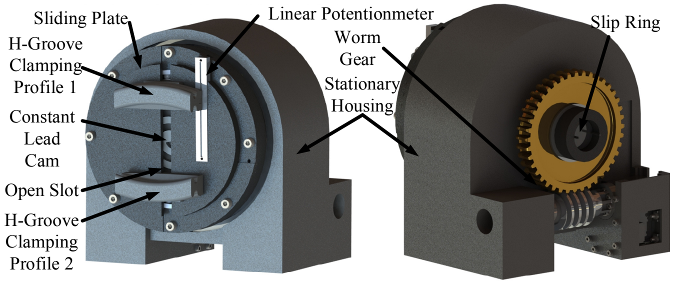

Figure 2. Mechanical design of GHEFT. Left: front view, Right: rear view

To connect an opposing coupling mechanism, the profiles are driven towards the midpoint of their respective slots. Docking is performed by engaging an opposing module from either the inside or outside of its clamping profile. One coupling mechanism will be engaged using the outside surface its clamping profiles while the opposing is engaged using the inside surface its clamping profiles. The clamping profiles are designed with one concave surface running about its width, and the second concave surface running about its length that is shaped with a large radius of curvature. This design feature enables large translational and angular misalignment tolerance as will be explained further in the next section. Although the clamping profiles have a radius of curvature about their length; once engaged, they will lock and provide a rigid connection since engagement of the profiles occurs at a distance less than their lengthwise radius of curvature. A perfect fit is ensured between clamping profiles whether engaged from the inner or outer surfaces that constrains translational and rotational motion between the modules. Since clamping profiles are engaged roughly in the midpoint of their respective sliding slots, disengagement can be achieved by sliding profiles either inwards or outwards depending on which surface is engaged. In the case of one-sided failure, disengagement can still be achieved by operating the functional coupling mechanism without collaboration from the malfunctioning unit.

Located at the rear end of the coupling mechanism is a worm gear assembly that provides high torque, non-back drivable relative rotation of the sliding plate with respect to the stationary housing. Depending on where the module is located within a robotic structure, this rotational DOF allows engaged modules to rotate with respect to one another to perform tasks such as locomotion, reconfiguration or manipulation. As seen in Fig. 3, the incorporated slip ring routs wires into the rotating hub allowing infinite rotation of the sliding plate without the risk of breaking wire connections. The coupling mechanism has a total of two degrees of freedom, relative rotation with respect to the stationary housing and translation of the clamping profiles.

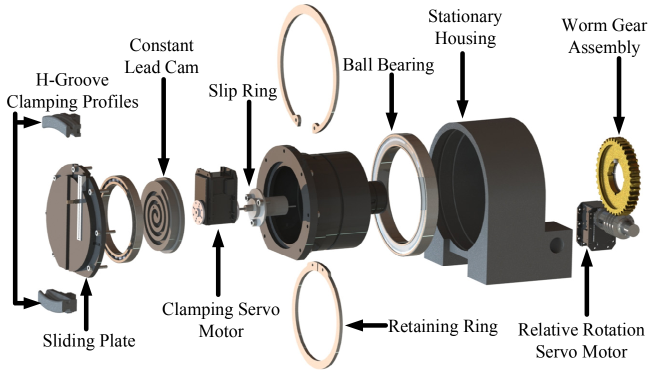

Figure 3. Exploded view of GHEFT design.

The clamping profiles of the GHEFT provide a genderless connection, allowing arbitrary modules to dock without any restrictions. The overall design provides a failsafe connection that can engage/disengage in the presence of one-sided malfunctions enabling the ability of self-repair. In addition, clamping profiles are designed to tolerate large misalignments and utilize large contact surfaces once engaged with an opposing coupling mechanism; thus, providing a high strength connection. An efficient connection is ensured due to non-back drivable actuation, no energy is required to maintain a connection resulting in low power consumption during operation. The combination of these design features provides modular self-reconfigurable mobile robots increased versatility, robustness and aids the process of self-reconfiguration.

MISALIGNMENT ANALYSIS

Misalignment tolerance is a necessary requirement for coupling mechanisms to perform successful self-reconfiguration and self-repair. Before modular robots dock, they must position themselves within close vicinity to a docking target. Then, they must perform fine alignment and positioning using the modules form of locomotion and integrated sensor feedback information (e.g. long range IR sensors, laser positioning systems, cameras, etc.). However, due to uncertainties in sensing, control, and the presence of un-modeled terrain, precise alignment is not possible. Since the probability of successful docking increases with larger misalignment tolerance, a coupling mechanism must be able to tolerate large translational and angular misalignments through its mechanical design. In three-dimensional space, misalignments exist in 6 DOF's. Translational misalignments $\{X, Y, Z\}$, and angular misalignments $\{\beta, \alpha, \gamma\}$ representing roll, pitch, yaw.

The GHEFT is capable of tolerating large misalignments using its specially designed H-grooved clamping profiles. As seen in Fig. 4A concave surfaces run along clamping profiles length and width. Each concave surface has local minima's and peaks. To illustrate how these surfaces contribute to misalignment tolerance, Fig. 4B shows a side view of two profiles during engagement that are initially misaligned in the positive X direction. Misalignments are tolerated under the initial condition that peaks of one profile are in contact with concave surfaces of the opposing profile. If so, clamping forces generated during docking will force the peaks to ride along concave surfaces and settle within their respective local minima.

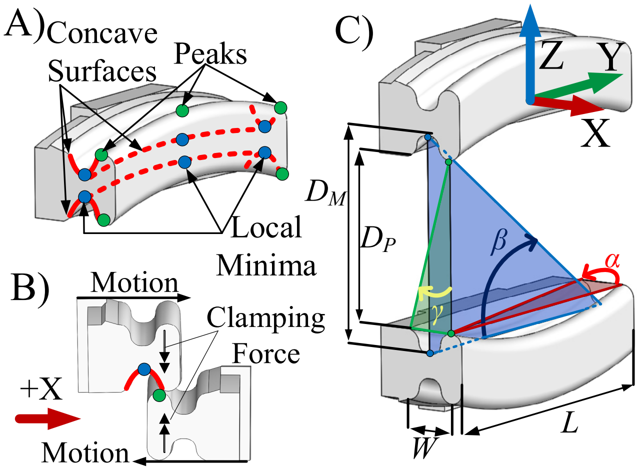

Figure 4. A) H-grooved clamping profiles depicting peaks, local minima and concave surfaces, B) Side view of engaged clamping profiles misaligned in X direction, C) Design parameters of clamping profiles in fully open configuration

Misalignment tolerance is highly dependent on the shape and dimensions of the clamping profiles. Figure 4C shows four design parameters of the H-grooved clamping profiles in a fully open configuration: W (width), L (length), D_P (peak-peak distance), D_M (minima-minima distance). Also illustrated are the resulting angular misalignment tolerances in the roll (β), pitch (γ) and yaw (α) dependent on dimensions of the design parameters. Using the previous explanation on how misalignments are tolerated under the initial condition that peaks and concave surfaces are in contact during engagement, simple relations may be formulated to calculate the maximum misalignment tolerance values. The maximum translational tolerances in the X and Y directions are equivalent to half the width and length of the clamping profiles $\{X=W/2,\ Y=L/2\}$;

while in the Z direction is equivalent to half the distance between two local minima $\{Z=D_M/2\}$. Assuming that two coupling mechanisms have no translational misalignments present during engagement relations can be derived expressing angular misalignment tolerance as a function of design parameters using trigonometric relations given by $\{\beta=\tan^{-1}(D_M/L),\ \gamma=\tan^{-1}(W/D_P),\ \alpha=\tan^{-1}(W/L)\}$. These relations represent the 6 DOF misalignment tolerances dependent on design parameters and can be used design clamping profiles to achieve specific tolerances based on application requirements.

The current clamping profiles designed for the GHEFT have the following dimensions: W=12.2, L=60, D_P=50, D_M=60. All dimensions are in millimeters. Table 1 presents the maximum, idealized misalignment tolerance capabilities using the formulated relations derived above.

Table 1. Maximum, idealized misalignment tolerance of GHEFT

Misalignment	X	Y	Z	ROLL	PITCH	YAW
GHEFT	6.1	30	30	45	13.7	11.5

Units: Translational misalignment (±mm), Angular misalignment (±°)

DYNAMIC SIMULATIONS

In order to measure the six DOF misalignments tolerance capabilities of the GHEFT; a physics based simulation package, Motion Analysis, from SolidWorks corp. was used. The objective of these simulations is to misalign the coupling mechanisms in each of the six DOFs to their maximum values, simulate docking, and observe if misalignments were tolerated.

Figure 4 shows the simulation setup of two GHEFT mechanisms initially separated by a translational misalignment about the X-axis. The mechanism on the left is actuated with closing clamping profile motion resulting in clamping profiles closing on the opposing, passive coupling mechanism that is free to rotate and translate in space. Physical contacts between clamping profiles, external walls and the floor were applied to simulate actual physical body interactions and movements of the virtual experimental setup. The maximum 6 DOF misalignments were determined by increasing translational and angular misalignments incrementally until successful docking failed. Table 2 summarizes dynamic simulations results of maximum misalignment tolerance. Results represent the maximum 6 DOF translational and angular misalignment errors that two mechanisms can tolerate to achieve successful docking. During the docking procedure, clamping forces produce relative motion that reduces translational and angular misalignment errors to zero.

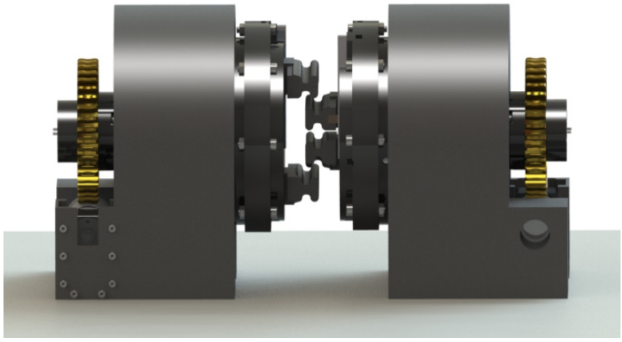

Figure 5. Simulation setup of two GHEFT mechanisms initially misaligned about the +X direction

Table 2. Dynamic simulation results of misalignment tolerance

Misalignment	X	Y	Z	ROLL	PITCH	YAW
GHEFT	6	28	11	45	13	11

Units: Translational misalignment (±mm), Angular misalignment (±°)

We notice that results from dynamic simulations fall slightly below those of maximum idealized misalignment tolerances computed in Table 1. This is expected due to large frictional forces resulting from body contact that prevent successful docking within the dynamic simulation. Z misalignment tolerance falls significantly below its maximum computed value since during the docking process, as the passive module was lifted up, it accumulated additional pitch misalignment in addition to its initial Z misalignment due to gravitational forces. This reduced the maximum misalignment tolerance in the Z direction obtained from the simulation.

CONCLUSION AND FUTURE WORK

This paper presented the development of a novel coupling mechanism that aids self-reconfiguration and self- repair for modular self-reconfigurable mobile robots. The GHEFT combines crucial design requirements such as being genderless, high strength, efficient, fail-safe, and tolerant to high misalignments into a small, compact mechanism.

Future work involves performing finite element analysis to demonstrate the proposed mechanism’s high strength and optimize the design of structural components for integration of a physical prototype. Experiments will then be conducted to obtain actual misalignment tolerances, validate results from dynamic simulation, and demonstrate both efficient operation and fail-safe capabilities of the GHEFT.

REFERENCES

[1] McPherson, Richard A., and Matthew R. Pincus. “Specific Protein.” Henry's clinical diagnosis and management by laboratory methods. Elsevier Health Sciences, 2011.

[2] Groß, Roderich, et al. "Autonomous self-assembly in swarm-bots." Robotics, IEEE Transactions on 22.6 (2006): 1115-1130.

[3] Moubarak, P.M.; Ben-Tzvi, P.; Zhou Ma; Alvarez, E.J., "An active coupling mechanism with three modes of operation for modular mobile robotics," Robotics and Automation (ICRA), 2013 IEEE International Conference on , vol., no., pp.5489,5494, 6-10 May 2013

[4] Cem Unsal and Pradeep K. Khosla, “Mechatronic design of a modular self-reconfiguring robotic system”, Proceedings of the 2000 IEEE International Conference on Robotics and Automation, San Francisco,CA, USA, pp.1742-1747, Apr. 2000.

[5] Satoshi Murata, Eiichi Yoshida, Akiya, Haruhisa Kurokawa, Kohji Tomita and Shigeru Kokaji, “M-TRAN:Self-Reconfigurable Module Robotic System”, IEEE/ASME Transactions on Mechatronics, Vol.7, No.4, pp.431-441, 2002.

[6] Akiya KAMIMURA, Satoshi MURATA, Eiichi YOSHIDA, Haruhisa KUROKAWA, Kohji TOMITA and Shigeru KOKAJI, “SelfReconfigurable Modular Robot-Experiments on Reconfiguration and Locomotion”, Proceedings of 2001 IEEE/RSJ International Conference on Intelligent Robots and Systems, Maui, HI, pp.606-612, Oct.-Nov. 2001.

[7] Toshio FUKUDA and Yoshio KAWAUCHI, “Cellular robotic system (CEBOT) as one of the realization of self-organizing intelligent universal manipulator”, Proceedings of the 1990 IEEE, International Conference on Robotics and Automation, Cincinnati, OH, USA, pp.662-667, May 1990.

[8] Keiji TOGAWA , Makoto MORI ,and Shigeo HIROSE, “Study on threedimensional active cord mechanism: development of ACM-R2”, Proceedings of the 2000 IEEE/RSJ International Conference on Intelligent Robots and Systems, Takamatsu, Japan, Vol.3, pp.2242-2247, Oct. 2000.

[9] A. Pamecha, C.-J. Chiang, D.Stein, and G. Chirikjian, “Design and implementation of metamorphic robots”, Proceedings of the 1996 ASME Design Engineering Technical Conference and Computers in Engineering Conference, Irvine, California, pp.1-10, Aug. 1996.

[10] D.Rus and M.Vona, “A basis for self reconfigurable robots using crystal modules”, Proceedings of IEEE Conference on Intelligent Robots and Systems, Takamatsu, pp.2194-2202, Oct.-Nov. 2000.

[11] M Yim, Y.Zhang and E.Mao, “Distributed control for 3D shape Metamorphosis”, Autonomous Robots, Vol.10, No.1, pp.41-56, 2001.

[12] Kotay Keith, Rus Daniela, Vona Marsette, McGray Craig, “SelfReconfiguring Robotic Molecule”, Proceedings of IEEE International Conference on Robotics and Automation, Leuven, Belgium, pp.423-431, May 1999

[13] S.Murata,E.Yoshida,H.Kurokawa,K.Tomita,andS.Kokaji,“ Self- repairing mechanical systems,” Autonomous Robots, vol. 10, no. 1, pp. 7–21, January 2001.

[14] Yim, Mark, David G. Duff, and Kimon D. Roufas. "PolyBot: a modular reconfigurable robot." Robotics and Automation, 2000. Proceedings. ICRA'00. IEEE International Conference on. Vol. 1. IEEE, 2000.

[15] P. Moubarak, P. Ben-Tzvi, "Modular and Reconfigurable Mobile Robotics", Journal of Robotics and Autonomous Systems, vol. 60, no. 12, pp. 1648-1663, December 2012.

[16] Yim, Mark, Ying Zhang, and David Duff. "Modular robots." Spectrum, IEEE39.2 (2002): 30-34.

[17] Guanghua, Zong, Deng Zhicheng, and Wang Wei. "Realization of a modular reconfigurable robot for rough terrain." Mechatronics and Automation, Proceedings of the 2006 IEEE International Conference on. IEEE, 2006.

[18] Moubarak, Paul M., and Pinhas Ben-Tzvi. "On the Dual-Rod Slider Rocker Mechanism and Its Applications to Tristate Rigid Active Docking." Journal of Mechanisms and Robotics 5.1 (2013): 011010.

[19] Murata, Satoshi, Kiyoharu Kakomura, and Haruhisa Kurokawa. "Toward a scalable modular robotic system." Robotics & Automation Magazine, IEEE 14.4 (2007): 56-63.

[20] Fu, Guoqiang, Arianna Menciassi, and Paolo Dario. "Development of a genderless and fail-safe connection system for autonomous modular robots." Robotics and Biomimetics (ROBIO), 2011 IEEE International Conference on. IEEE, 2011.

[21] Shen, Wei-Min, Robert Kovac, and Michael Rubenstein. "SINGO: a single-end-operative and genderless connector for self-reconfiguration, self-assembly and self-healing." Robotics and Automation, 2009. ICRA'09. IEEE International Conference on. IEEE, 2009.

[22] J. W. Suh, S. B. Homans, and M. Yim, “Telecubes: Mechanical design of a module for self-reconfigurable robotics,” in IEEE Intl. Conf. on Robotics and Automation (ICRA), 2002, pp. 4095–4101.

[23] S. Murata, E. Yoshida, A. Kamimura, H. Kurokawa, K. Tomita, and S. Kokaji, “M-TRAN: Self-reconfigurable modular robotic system,” IEEE/ASME Transactions on Mechatronics, vol. 7, no. 4, pp. 431– 441, December 2002.

[24] S. Goldstein, J. Campbell, and T. Mowry, “Programmable matter,” Computer, vol. 38, pp. 99–101, May 2005.

[25] V. Zykov, E. Mytilinaios, B. Adams, and H. Lipson, “Self-reproducing machines,” Nature, vol. 435, no. 7038, pp. 163–164, 2005.

[26] Shen, W.-M. and P. Will. Docking in Self-Reconfigurable Robots. In Proc. 2001 IEEE/RSJ Intl. Conf. on Intelligent Robots and Systems, pp. 1049–1054, 2001.

[27] Castano, A. Behar, and P. Will, “The Conro modules for reconfigurable robots,” IEEE/ASME Trans. Mechatronics, vol. 7, no. 4, pp. 403–409, December 2002.

[28] M. Yim, Y. Zhang, K. Roufas, D. Duffa, and C. Eldershaw, "Connecting and disconnecting for chain self-reconfiguration with polybot," IEEE/ASME Transactions on mechatronics, special issue on Information Technology in Mechatronics, 2003.

[29] S.Murata,E.Yoshida,H.Kurokawa,K.Tomita,andS.Kokaji," Self- repairing mechanical systems," Autonomous Robots, vol. 10, no. 1, pp. 7–21, January 2001.

[30] M. Jørgensen, E. Østergaard, and H. Lund, "Modular atron: Modules for a self-reconfigurable robot," in IEEE/RSJ Int. Conf. on Robots and Systems, Sendai, Japan, 2004, pp. 2068–2073.

[31] C. Unsal, H. Kilic¸c¸ote, and P. K. Khosla, "A modular self- reconfigurable bipartite robotic system: Implementation and motion planning," Autonomous Robots, vol. 10, no. 1, pp. 23–40, January 2001.

[32] F. Mondada, M. Bonani, S. Magnenat, A. Guignard, and D. Floreano, "Physical connections and cooperation in swarm robotics," in 8th Conference on Intelligent Autonomous Systems (IAS8), 2004, pp. 53– 60.

[33] V. Zykov and H. Lipson, "Fluidic stochastic modular robotics: Revisiting the system design," in Proceedings of Robotics Science and Systems Workshop on Self-Reconfigurable Modular Robots, Philadelphia PA, August 2006.

[34] M. Nilsson, "Connectors for self-reconfiguring robots," IEEE/ASME Transactions on mechatronics, vol. 7, no. 4, December 2002.