

## Lightweight Means of Actuation for Use in Space-Based Robotics Applications

Scott P. Brady\*<sup>a</sup>, Xiu T. Yan\*<sup>a</sup>

a) Space Mechatronic Systems Technology Laboratory, University of Strathclyde, Glasgow, Scotland.

\* Corresponding author

### Introduction

Robotics in the modern world are implemented in a range of applications, with the key characteristics of systems also being subject to wide variance depending on the application. As part of the study of an ongoing endeavour, a key characteristic under scrutiny is that of lightweight robotics; in particular, how that pertains to the actuation package of such mechatronic manipulation devices.

Varying studies have taken place detailing the effects of reducing weight in a system and how this is beneficial. Two of the most prominent reasons for developing lightweight robotic systems are for safety reasons and for reasons of cost effectiveness. Safety seems fairly self-explanatory: a system which doesn't adversely affect the well-being of a human working nearby. As robots are set to see greater autonomy in their operation perhaps the question should not relate just to how robots can damage an actual person, but their effect on surroundings and the surroundings effects on humans. Cost effectiveness can be rendered through physical material costs and standardised manufacturing methods, but, more pertinent to space-based activities, the reduction of weight can also reduce in logistics costs – costs associated with shipping into space run into the many 10s of thousands of

dollars/kg, therefore reduction of weight = reduction of cost.

This work is part of a larger scale project, but within this paper a certain number of points will look to be addressed. Some brief history of lightweight robotics will be reviewed, as well as discussion some of the state-of-the-art technologies. Doing so allows a fluid Segway into analysis of the key components and architectures of lightweight robots and robots more generally. Developing the argument in this way allows for some observations to be made which should hopefully provoke thought and discussion on the topic. Following review of the existing methods, the paper will then look to delineate the technologies available to the robot designer, discussing and commenting on how these technologies could perhaps be used in order to; this discussion will try to avoid myopic discussion, looking to how the technology could assist robotic undertaking not only in the very near future, but also further down the road. This will allow content at various TRLs (technology readiness levels) to be addressed and, thus, further promote discussion and innovation. Finally, some of the future contributions which are presently under development by this paper's authors will be discussed and critiqued.

## Benefits of and Justification for Pursuance of Lightweight Robotic Systems

As already mentioned, there are two key reasons for the development of lightweight robotics pursuant to this project. These are improved safety and reduced cost (where cost applies both to the fiscal impact, but also to the depletion/retention of energy (and other resources)).

### Safety

There is a wealth of information on the subject of human safety when working in close proximity to robots, mainly due to the ever increasing trend towards closer collaborative working between both sets of “agents”. The robot population of factories and manufacturing centres globally is something which is ever increasing, so the trend towards improved safety in human-robot interactions is of great benefit to many stakeholders on a truly global scale. Arguably, this is why good progress has been made in this area in recent history – the numbers of people and organisations who stand to gain from it. Indeed from the inception of robotics the safety of humans around such systems has been a priority: *a robot must not injure a human being or, through inaction, allow a human being to come to harm* (Asimov, 1953).

In review, these authors have encountered a variety of works which deal specifically with safety of robotics in contact with humans. Many of the works encountered deal with the development of new algorithms and control strategies which would enable the robot to operate more compliantly and with a greater degree of awareness. However, there are mechanical modes through which this could also be achieved if certain principles are followed or, at least, considered to some degree in a systems design.

The effects of the LWRiii when in collision with humans are detailed in one paper (Haddadin, Albu-Schäffer, & Hirzinger, 2008) (Haddadin,

Albu-sch, Frommberger, & Hirzinger, 2008) and the results seemed to suggest that a collision with a human where a human appendage isn't “clamped” is very unlikely to cause fatality or severe injury. The results also indicated that for varying weights of robot the risk can be managed by attenuation of the velocity of the arm. Of course, ideally there wouldn't be a trade-off. One point to consider is also that this information and other tests like it are only reviewing the impact on a human body, which is after all a highly compliant structure, capable of bending and absorbing energy. Haddadin *et al.* discuss how injuries can be attenuated if a 10kg robot is driven no faster than approximately 5.5m/s and no faster than 3.5m/s for a 100kg robot. All the evidence seems to support this claim that a human would not be subject to injury in the event of an unclamped collision at these speeds; however, the forces generated by such a collision are not insignificant and the effects they could have on key components of their surroundings could potentially be detrimental. If some of these surroundings happen to be important apparatus or critical equipment then damage to it is obviously something which would rather be avoided; i.e. a robot arm hitting an astronaut might not cause much damage, but a hit to an EMU, MMU or other piece of space-based apparatus, for example, might have more severe effects..

### Equations to back up.

In the event of clamping mass is shown to have a much greater role and can generate forces which are likely to cause serious injury or fatality. It has been discussed how the safety impact on humans can be an issue by direct contact with a human, and previous studies have attempted to quantify this – and have done so quite well. Another issue delineated is that of robot effects on environment and the knock on effects that can have on those operating in or near than environment. Demonstrably then, the weight of a robotic arm is a factor in the safety of humans operating near them, be that in space or

terrestrially. The degree to which the weight is a factor is somewhat debatable; however, it is a parameter in the discussion.

### Cost

As already alluded to, the cost of a system can be considered purely from the fiscal perspective in terms of its material, hardware, manufacture, and logistics costs; however, it would be argued that as an adjunct to this the costs from an energy expenditure perspective should also be given due consideration.

It can be stated that heavier robots are more likely to require the use of more material in order to support static and dynamic loading or linkages, or that the manufacturing methods to develop these could be more expensive. These are, however, fairly blithe statements which can be refuted with clever design and engineering of a system. More difficult to refute is the effect on hardware of a heavier system. If a robot arm is heavy, then the motors and gearing assembly require to provide adequate positioning power to the arm is very likely to be either heavier or more costly. Both drive up two parameters which in the instance of this work are being attempted to attenuate. Going beyond the basic capital cost of such motors (in terms of weight and currency), there is an intrinsic knock-on effect here to be considered also: the energy cost. The heavier the arm is, the more work will be required to move it, and, thus, the more power and energy will be needed in order to achieve the desired movement of the system under consideration.

One of the first cost-based considerations encountered in this research project was that of the cost of logistics; i.e. how much does it cost to send items into space. The first figures encountered on the cost of shipping to space came in at around £X/kg shipped into space. Since then some advances have taken place, most notably the capability to reuse rockets for space travel. Taking these into account the most recent figures encountered are around \$20,000 per kilogram at the cheapest estimate

for a fully loaded SpaceX Dragon. For perspective, this would mean a bottle of water costs ~\$10,000 and upwards to ship to space. The effects of a heavier robot arms on logistics costs can be easily appreciated, and the significance of weight reduction observed.

### Modern Lightweight Solutions for Robotic Use

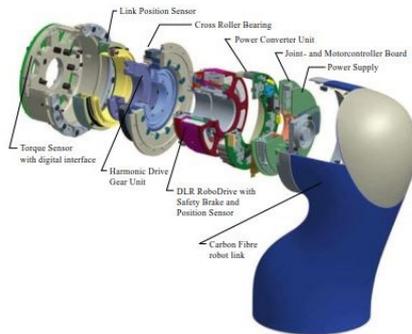
In this section the paper will digress from bespoke conversation on space-based activities and look to existing examples of lightweight robotic systems. Examination of these systems was undertaken in the review process in order to ascertain the capabilities of lightweight systems currently in operation. These are subdivided into discrete, serpentine, and continuum systems as first discussed by Robinson and Davies (1999), where discrete systems have distinct joints and linkages, continuum robots have no distinct joints or links and operate as muscular hydrostats (think of an elephant's trunk). Serpentine robots are essentially in the middle, where joints and links exists but they are numerous and small, much like a snake's body – it has a boned structure which rotates on joints, etc.

### Discrete Systems

When one thinks of a robot arm what is considered is often a discrete system – a typical articulated robot which operates in manufacture and assembly operations. The DLR LWR series of robots are arguably the best-in-class discrete robots. The KUKA LWRiii, for example, has a weight to load ratio of 0.47 (16kg weight and 7.52kg load capacity), which is fairly typical for designs of this type and its close competitors. Generally speaking, the load to weight ratio of the system is amongst the best in use.

Unlike other systems (which will be discussed imminently) all of the drive, transmission, sensory apparatus is intrinsic to the robot arm; i.e. it is embedded in the arm and not external to the arm. Intrinsically actuated robot arms have no “gross” weight advantage over their extrinsically actuated counterparts; however,

intrinsic actuation of an arm does mean that the arm itself is likely to be heavier. Review of the interior cross-section of the drive system of such robots goes some way to explaining why this might be the case, see figure 1.



**Figure 1: Exploded view of mechatronic joint assembly from DLR LWR. Reproduced here with permission from author.**

Figure 1 clearly demonstrates the amount of equipment which is embedded in a robot arm. The assembly consists of a number of components, virtually all of which have substantial weight to them; it wouldn't be terribly inaccurate to describe the motor, roller bearing, and harmonic drive as lumps of metal, whilst the other sub-assemblies are constructed of varying other components all cumulatively contributing to the system mass. The thing to consider is that in the example shown in figure 2 is that only 1 joint is shown. This joint or joints of similar credentials tend to be replicated around 6 times, obviously meaning that the joint weight is replicated 6 times before other parts of the system are even considered.

It is well understood that this is a common design trait of articulated robots, but the observation made by this researcher is that challenging this paradigm may allow for improvement in weight to load ratios. From a first principles approach to the problem, then, this researcher would question whether there may be another means of addressing the actuation of each joint which **doesn't require a motor which is exclusive to each joint**, or at least doesn't require quite as much apparatus per joint. The feasibility of this seems quite

questionable; however, it would be an interesting endeavour to explore how the existing components in different combinations, or potentially newly developed mechanisms, might be able to positively influence robotic operation from a weight reduction perspective, as proposed.

Extrinsic actuation (Robinson & Davies, 1999) would appear to be one mechanism through which some reduction in weight of the **arm** might be achieved; however, as long as each joint still requires an individual motor and/or elaborate set of apparatus to control and power the joint then the system cost will still be high in terms of weight. Such technology is typically applied to serpentine and continuum robot manipulators; however, there are some successful examples of it being applied to discrete designs, most notably the Iqus Robolink design, which is a modular robot arrangement where joints are controlled by the tensioned cables with the controlling motors for these in a housing external to the arm; a good example of extrinsic actuation already discussed.

### Serpentine and Continuum Systems

Having already introduced the idea of extrinsic actuation, we move now to two examples of robotic systems which tend to be operated quite commonly by this method. Robots utilising this method of actuation tend to have lightweight arm assemblies, although most of the instances of these types of robot encountered in literature tend to be experimental developments with limited capabilities. Although there are differences between the two, there tends, it seems, to be a tendency to lump both together under the colloquial heading of snake-arm robots, owing to the manner in which they operate.

It has been difficult to find any specific information on the exact characteristics of weight, load to weight ratio, etc. as they don't have bespoke brochures the way that discrete systems which are routinely employed in industrial settings do. It has been found,

however, that many of the actuation modes utilised tend to have a high strength to weight ratio. It has been described how pneumatic artificial muscles (PAMs) of the McKibben actuator type have high strength to weight ratios, and the use of tendon arrangements and twisted string actuation has also been discussed as having an excellent ability to convert low power inputs into large force translations. In this regard, these robots are similar to the Robolink in that they are reducing weight of the arm itself, but the “gross” weight of the system is still fairly unchanged (there may be slight reductions due to lighter arm and, therefore, less rigorous motor requirements); the actuators, power supplies, encoders, etc. are all still part of the system, they just happen to be outwith the arm. Relative to the problems discussed already, it would be argued that this extrinsic mode of actuation helps to reduce the issue of safety concerns as the arm (the member which is likely to cause damage to a person or apparatus) is able to be reduced in weight. As the gross weight is relatively unchanged, however, the issue of logistic cost remains unchanged. With reduced arm weight comes the possibility of reduced motor requirements and also reduced energy requirements.

The use of intrinsic and extrinsic actuation as a set of principles on is not sufficient to consider, so thorough review of all encountered actuation methods available has taken place in order to thoroughly assess what tools are at the researcher’s disposal as he attempts to make progress in the defined area. Herein such methods will be briefly reviewed, before discussion of proposed work and work completed so far is addressed.

### Technology to be Exploited

This section will summarise the potential modes by which the actuation of a robotic system can be achieved and efforts will be made to make evidence-based claims pursuant to the advantages of these methods *visa-vi* the reduction of weight.

### Direct Drive Electric Motors

The most obvious means of achieving robotic motion. This method has been mentioned implicitly during review already when discussion regarding the DLR LWR and discrete systems more generally. As far as the use of motors for direct drive (and other augmentations of motors and associated apparatus being embedded in joints) is concerned in relation to lightweight robotics it is difficult to see beyond the continuing paradigm of incrementally increasing capabilities and reducing weight of motors. Enhancement of motor, sensor, transmission, etc. technology will obviously be beneficial, but these means would best be described as incremental improvements.

Possible exception may relate to the development of motors utilising non-traditional materials. For example, some authors have discussed the feasibility of 3D printing motors for self-replicating machines using shape memory polymers (SMPs) in order to achieve the required movement (Ellery, 2016) (Ellery, 2015). Use of such materials may result in reduction of weight by enabling printing of honeycomb structures in the support members, or by the materials themselves being of lesser mass per unit weight. This author’s opinion on this encountered idea is that the TRL of this method seems extremely low, and though the concept is intriguing, it appears to be some way from being realised.

### Pneumatic/Hydraulic Artificial Muscles

Again, PAM/HAM concepts have already been discussed. Essentially, this idea involves the changing of pressure of an artificial muscle “pouch”. It has been discussed already how some authors advocate the use of PAM concepts on the grounds that they are very capable and offer excellent force output to weight ratio. A caveat that this author would add to this is that it would seem that the weight mentioned in these instances refers only to the bladder containing the air. This

suspicion is borne of the knowledge of the apparatus required external to the bladder in order to provide the increased airflow to generate said pressure. This is an addition to varying other hardware required to control the process.

Another point worthy of mention is that the **hydraulic artificial muscles** do not comply to these same set of criteria relative to weight. PAM concepts utilise air, which is obviously negligible mass in most practical instances. HAM concepts, however, utilise hydraulic fluid, which in some cases can be heavier than water, owing to the required density of the fluid. HAM concepts virtually are a non-starter in lightweight applications, unless they could be appropriated in some novel manner

Ultimately, PAM and HAM concepts might be very useful for terrestrial applications and certainly offer a multitude of benefits when being applied to continuum robots in particular – continuum designs seek to emulate muscular hydrostats, such as a tongue or an elephants trunk, so PAM/HAM concepts are very alike these natural phenomena. This author would argue against their use in space-based activities for the following reasons. HAM concepts, as mentioned, are a non-started owing to their weight. PAM concepts can require heavy apparatus, etc. for pumps; however, the use of air in space may also add unnecessary complexity. This author's suspicion is that for the same weight a more effective system could be developed.

### Tendon-Based Actuation

The idea of extrinsic actuation is something which has already been discussed, and this author believes that (particularly in instances where extreme accuracy and repeatability are not essential – inspection tasks, for instance) extrinsic actuation would be a very valuable tool at a designers disposal. Tendon-based actuation provides the means to achieve this. As already posited this would enable removal of large amounts of weight from the arm, but still presents the issue of simply having

“moved” the weight from one part of the system to another, which is a less significance in making a positive impact relative to logistics costs. Development of truly novel actuation methods may find some way of yielding more substantial reduction of weight in the drive element of the system.

Igus' Robolink design has made excellent use of the principle under discussion. Variation on this theme should enable, if not a single versatile solution to many problems to be developed, the development of varying concepts which can be utilised depending on the application. For instance, this author intends to carry out some experimental work involving the removal of motors and transmission from joints, but trying to leave sensory apparatus embedded in the joint. Doing so may enable arm weight to be significantly reduced whilst maintaining acceptable degrees of accuracy.

The concept of twisted string actuation (TSA) is another concept which has been encountered during review of the literature on robotics. This technology involves twisting one or (more commonly) 2 or more strings around one another, by which the outcome is that this rotational twisting results in a shortening of the strings in a linear direction and, hence, a linear force is applied. Again, there are a number of authors who speak very highly about the potential applications of this due to its simplicity, its low weight, and its high force to weight ratio. It has also been shown to exhibit good accuracy and durability. A possible set-back of this idea may be the limited range that it has. However, some researchers have overcome this issue by utilising the method in a bi-directional antagonistic arrangement, allowing large movement in a rotational direction about joints through small displacements in linear movement (Popov, Gaponov, & Ryu, 2013a) (Popov, Gaponov, & Ryu, 2013b) Utilised in conjunction with other actuation methods may make this method a more viable means of achieving a repeatable, accurate, cheap, and lightweight mode of

actuating a mechatronic manipulation system. During review of TSA various augmentations of the technology have been encountered, the most noteworthy of which is an innovative clutched drive system for twisted string actuation

### **Tensegrity Structures**

A truly novel notion – and one for which there is not much literature on – is the prospect of a tensegrity structure utilised as a robotic manipulator arm. Tensegrity structures are systems comprised of rigid and compliant members which are in compression and tension, respectively. The result is a structure with many excellent engineering traits, which appears to float in some places. This type of structure was initially utilised in works of art, but recently its applicability to engineering endeavours has been explored.

The systems are extremely lightweight and offer excellent potential for high force transfer, whilst also offering an extremely robust, yet compliant morphology. The downfall is that this is pretty much an entirely new concept, with the potential to truly pioneer this technology. Therefore, it goes without saying that the TRL of this idea is extremely low. From the little work that has been carried out in this area, it is discernible that the process of controlling the system is extremely complex. Owing to the relative members being in compression and tension – and that the members cross one another throughout the structure – attempting to evoke the correct movement appears to be very difficult. Accuracy and repeatability then also become big issues once movement is achieved.

### **Layer Jamming and Granular Jamming**

Layer jamming and vacuum jamming are two experimental methods encountered during research which enable the, which make use of vacuum forces in order to control the 3-dimensional motion of a body. They are two modes through which stiffness can be adjusted, essentially. For this they are

sometimes referred to as members of a subset of variable stiffness actuators (VSAs).

Granular jamming has been exhibited to show its applicability as a means of grasping objects without the need for complex object recognition (Brown et al., 2010) (Amend, Brown, Rodenberg, Jaeger, & Lipson, 2012). The technology operates on the principle of interfacing a bladder full of loosely packed granulated material. Once in contact with an object this loosely packed material will deform around the object. At this stage, a vacuum is applied which pulls the loosely packed material tightly together. In so doing, the now tightly packed granular media has grasped the object firmly. This is an interesting notion; however, more interesting is the work of other researchers where the same principle has been applied to manipulation endeavours (Cheng et al., 2010). This robot is essentially a continuum robot; however, the use of granular media allows local stiffness to be achieved to help resolve robots associated with this robot type. As with other modes explored, the TRL of this technology type appears to be quite low

### **Electroactive polymers (EAPs), Shape Memory Alloys (SMAs) and Shape Memory Polymers (SMPs)**

EAPs, SMAs, and SMPs are all subsets of a category of material which is driven by external stimulation. When exposed to these stimulants the materials deform to make a pre-programmed shape. The capacity to do this is extremely innovative and removes the necessity for a large amount of apparatus including transmission systems, numerous motors, etc.

EAPs have been discussed as having excellent credentials in their resilience, ability to effect large actuation strains, and their likeness to biological muscles (Bar-Cohen, 2001); they are, essentially, artificial muscles. This type of actuation can be well-tailored to the needs to the needs of the application and is cost-effective (Pelrine, Kornbluh, Pei, & Joseph, 2000). This type of actuation method is very

applicable to continuum robot types, owing to the hyper-redundant capabilities for movement. Additionally, this type of technology is noted by some authors as being a better alternative to SMPs, SMAs, and EACs (electro-active ceramics) owing to faster response times, lower density, and greater resilience (Bar-Cohen, 2001).

SMPs and SMAs operate in similar manner to EAPs, also offering the capacity for variable stiffness actuation. Again, these modes are charged by electrical stimulants. Instances of SMPs/SMAs have been used to mimic human hand movements, with demonstrable results evoking some characteristics which are similar to those of a human hand (Maeno & Hino, 2006). Shape memory applications offer the possibility of assisting in approaching tasks which require complex manoeuvring of systems (Mineta et al., 2002). As with others, this technology is at a fairly low TRL.

Ultimately, the responses of these systems appear to be questionable in their controllability and their force transmission abilities; however, further development of new polymers may open up other avenues of exploitation in this regard. Should this be achieved, the modes discussed in this section would allow lightweight and hyper-redundant robots to be developed which are, as one author put it “the thing of science fiction”.

#### **Electrorheological and Magnetorheological Methods**

ER and EM methods offer the means to variable stiffness actuation of systems. Bar-Cohen discussed in 2001 how ER and EM methods could be used as effective damping measures for systems in robotic applications. Similarly, other researchers have successfully utilised homogeneous ER fluids in order to more effectively control position of end effectors to a very precise level (Takesue, Zhang, Furusho, & Sakaguchi, 1999).

ER and EM methods have not been encountered often in review, but the works

encountered seem to suggest that they offer potential as far as reduction of vibration, and precise positioning of apparatus. The question of their applicability to lightweight robotics depends largely on their application; however, large scale use of fluids is unlikely to be beneficial to lightweight applications for the same reasons which applied to hydraulic applications.

#### **Proposed Works**

As a result of the work which has been undertaken several knowledge gaps have been identified, some of which have been alluded to in the writing of this article. Relative to the knowledge gaps encountered and the researcher’s own preferences and interests two main contributions are under development and will be discussed herein.

#### **Contribution 1**

Firstly, the whole process of literature review has inspired the development of a taxonomy of actuation and, consequently, an assisted selection technique for actuation of mechatronic manipulation. As technology progresses the variance in possibilities for actuation of a system also progresses and becomes more diversified. This presents an issue to those coming in at the bottom of the industry, as engineering students and also professional engineers are unlikely to be familiar with some (or any) of the options available to them. The innovation here is to develop new mode of categorising the different types of actuation available to the student, engineering designer, or researcher and take it to the next step. The next step which will be taken is to develop what is a basic categorisation of the options available to a mechatronic system designer and attempt to quantify the various components such that depending on the system requirements the job of choosing the correct components is simplified; i.e. be delineating the differences between AC Brushed and DC Brushless motors, different types of transmission system, and different types of sensory apparatus it may be

possible to assist designers in the development of mechatronic systems. Similarly, completion of this process may also result in a helpful reference tool to be utilised by students and academics in the initial throes of engineering endeavour.

## Contribution 2

The second contribution to be put forth as a result of this project is the development of 2 new actuation mechanisms. Explanation of the principles of these actuators requires a somewhat clandestine explanation, so as not to give too much about the premise away. As has been iterated many times, this research has covered literature and found the prospect of an extrinsically actuated system to be one which would be very effective in reducing arm weight. Similarly, the prospect of reducing the number of mechanical components utilised per degree of freedom is also an alluring idea.

## Conclusion

In an ideal world, robotic arms would be weightless with infinite load manipulation capacity, repeatability, and accuracy, etc. This obviously is far beyond the capabilities of the technology available now; however, by continuing the push the boundaries of what is capable, and by approaching problems with new degrees of innovation, this distance from this ideal scenario can be reduced. Whilst solutions developed hitherto have many characteristics which made them excellent in the completion of certain activities, there is still potential for improvement in their operation; i.e. they could be cheaper, lighter, improved weight to load ratio, better versatility, and myriad other enhancements. Not only that, but some issues are still unsuitable for robotic application due to low TRL of technology or because of not solution even having been conceived of.

In this paper some of the best in class and typical existing solutions for robot problems have been covered briefly, and following this a high level breakdown of the technology used in

robotics currently and the technology available in the future has been discussed. The intention of this paper was to complete a review of the literature stage of an ongoing project and through doing so to provoke thought and discussion on the topic of actuation for lightweight robotic systems. Throughout this paper, critique has taken place with respect to some of the existing issues behind the mechanical design and implementation of robotic systems, particularly as it pertains to lightweight robotics. It is hoped that in doing so it may provide other researchers with the innovation required to consider approaching some of the points made and to attempt to further knowledge in these areas. Furthermore, the contributions which will be made as part of this project have also been laid out and the manner in which they will be useful to the community discussed.

## References

- Amend, J. R., Brown, E., Rodenberg, N., Jaeger, H. M., & Lipson, H. (2012). A positive pressure universal gripper based on the jamming of granular material. *IEEE Transactions on Robotics*, 28(2), 341–350. <https://doi.org/10.1109/TRO.2011.2171093>
- Asimov, I. (1953). *The Caves of Steel*. Doubleday.
- Bar-Cohen, D. Y. (2001). Electroactive Polymers as Artificial Muscles – Reality and Challenges Yoseph Bar-Cohen NDEAA Technologies, JPL / Caltech, Pasadena, CA. *Proceedings of 42nd AIAA Structures, Structural Dynamics, and Materials Conference (SDM)*.
- Brown, E., Rodenberg, N., Amend, J., Mozeika, a., Steltz, E., Zakin, M. R., ... Jaeger, H. M. (2010). From the Cover: Universal robotic gripper based on the jamming of granular material. *Proceedings of the National Academy of Sciences*, 107(44), 18809–18814. <https://doi.org/10.1073/pnas.1003250107>

- Cheng, N. G., Lobovsky, M. B., Keating, S. J., Setapen, A. M., Gero, K. I., Hosoi, A. E., & Iagnemma, K. D. (2010). Design and Analysis of a Robust, Low-cost, Highly Articulated Manipulator Enabled by Jamming of Granular Media. *Proceedings of 2012 IEEE International Conference on Robotics and Automation (ICRA)*, 4328–4333.
- Ellery, A. (2015). Notes on Extraterrestrial Applications of 3D-Printing with Regard to Self-Replicating Machines \*, 930–935.
- Ellery, A. (2016). Are Self-Replicating Machines Feasible? *Journal of Spacecraft and Rockets*, 53(2), 317–327. <https://doi.org/10.2514/1.A33409>
- Haddadin, S., Albu-sch, A., Frommberger, M., & Hirzinger, G. (2008). The Role of the Robot Mass and Velocity in Physical Human-Robot Interaction - Part II : Constrained Blunt Impacts, 1339–1345.
- Haddadin, S., Albu-Schäffer, A., & Hirzinger, G. (2008). The role of the robot mass and velocity in physical human-robot interaction - Part I: Non-constrained blunt impacts. *Proceedings - IEEE International Conference on Robotics and Automation*, (11838), 1331–1338. <https://doi.org/10.1109/ROBOT.2008.4543388>
- Maeno, T., & Hino, T. (2006). Miniature five-fingered robot hand driven by shape memory alloy actuators. *Proceedings of the 12th IASTED International Conference, Robotics and Applications*, 174–179. Retrieved from <http://www.actapress.com/PaperInfo.aspx?PaperID=27970&reason=500%5Cnhttp://www.actapress.com/PDFViewer.aspx?paperId=27970>
- Mineta, T., Mitsui, T., Watanabe, Y., Kobayashi, S., Haga, Y., & Esashi, M. (2002). An active guide wire with shape memory alloy bending actuator fabricated by room temperature process. *Sensors and Actuators, A: Physical*, 97–98, 632–637. [https://doi.org/10.1016/S0924-4247\(02\)00021-3](https://doi.org/10.1016/S0924-4247(02)00021-3)
- Pelrine, R., Kornbluh, R., Pei, Q., & Joseph, J. (2000). High-Speed Electrically Actuated Elastomers with Strain Greater Than 100%. *Science*, 287(5454), 836–839. <https://doi.org/10.1126/science.287.5454.836>
- Popov, D., Gaponov, I., & Ryu, J. (2013a). Bidirectional Elbow Exoskeleton Based on Twisted-String Actuators, 5853–5858.
- Popov, D., Gaponov, I., & Ryu, J. H. (2013b). A preliminary study on a twisted strings-based elbow exoskeleton. *2013 World Haptics Conference, WHC 2013*, 479–484. <https://doi.org/10.1109/WHC.2013.6548455>
- Robinson, G., & Davies, J. B. C. (1999). Continuum Robots - A State of the Art. *Robotics and Automation, 1999. ...*, 4(May), 2849–2854. <https://doi.org/10.1109/ROBOT.1999.774029>
- Takesue, N., Zhang, G., Furusho, J., & Sakaguchi, M. (1999). Precise Position Control of Robot Arms Using a Homogeneous ER Fluid. *IEEE Control Systems*, 19(2), 55–61. <https://doi.org/10.1109/37.753936>