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Embodied Intelligence & Morphological Computation in Soft Robotics Community: Collaborations, Coordination, and Perspective

S.M.Hadi Sadati[1†*], Marwa ElDiwiny[2†], Surya Nurzaman[3], Fumiya Iida[4], Thrishantha Nanayakkara[5]

[1]The Robotics and Vision in Medicine Lab, School of Biomedical Engineering & Imaging Sciences, King's College London, UK.
[2]Brubotics, Vrije Universiteit, Brussel, Belgium
[3]Mechanical Engineering Discipline, School of Engineering, Malaysia Campus, Monash University, Melbourne, Australia.
[4]Machine Intelligence Laboratory, Department of Engineering, Cambridge University, UK.
[5]Dyson School of Design Engineering, Imperial College London, UK.
[†]Equal contributions.

E-mail: *smh_sadati@kcl.ac.uk

Abstract. The agile nature of physical interactions in animal and plant species has inspired many recent advances in robotics and their control frameworks. However, they still face challenges in interaction with ever-changing unconstructured world that we live in. Intelligence is one of nature's survival solutions for biological creatures to adapt to and reshape their surroundings. Our robots are no different in these remits. An important key to their survival and effectiveness in the natural world is the concept of Artificial Intelligence (AI). In this chapter we provide a brief overview of the rapidly emerging Soft Robotics research community around AI relevant concepts such as Embodied intelligence and Morphological Computation. More specifically, we focused on the importance of setting such "*community goals*" to create a diverse interdisciplinary research environment, an enormously important element to keep up with our rapidly progressing world. To this end, we focused on the collaborations withing and between the communities, impacts of the recently established IEEE Soft Robotics Technical Committee on coordinating these efforts, and most important of all, the key ideas and perspectives based on 200 interviews with researchers across different fields.

1. Introduction

Animals can solve realtime computational problems to do with perception and action in a natural world that robots find it hard to solve. Realtime computation means solving computational problems to come up with good enough answers to meet deadlines imposed by the environment. i.e. If a mountain goat slips on a steep cliff, it has to brake before the momentum builds too much. The problem of braking before it is too late is imposed by the environment. The solution clearly cannot come from the nervous system alone due to its slow communication pathways. Then an embodied solution to use passive dynamics is needed [1]. Similar problems are faced by humans performing object examination such as checking if a fruit is ripe or not or a steak is well cooked or not using haptic feedback. They have to find a finger stiffness and movement control strategy to perceive before it is too late to take the correct decision [2].

There is an increasing interest among the robotics community to use biological inspirations to exhibit efficient, robust, and compliant behavior [3]. In many notable bioinspired robotic examples [4], there is no clear boundary between biomechanical and sensor based control algorithms [5]. In other words, the "controller" and "controlled" are not explicitly detached from one another [6]. For instance, [7] addresses this integrated/embodied approach by use of "templates and anchors" where some of the control task is delegated to passive dynamics of the physical body. Related examples such as the RHex robot [8], the pure passive dynamic model of a goat's hoof with no sensors or actuators for slip reduction [1], and various models of passive dynamic walkers [9] suggest that the notion of control can take many forms that includes benefiting from passive dynamics of physical systems.

In other words, the brain and the body should work together to overcome challenges of our unstructured world to achieve extremely robust, energy efficient, and highly adaptive robots similar to biological systems [10]. This hints interesting paradigms for

- *Embodied intelligence* (EI), "investigating tight coupling between an agent body and brain"[11],
- *Physical intelligence* (PI), "physically encoding sensing, actuation, control, memory, logic, computation, adaptation, learning and decision-making into the body of an agent" [11], and
- *Morphological Computation* (MC), "outsourcing part of control, sensing and computation tasks to the robot body to be handled through emergence of functional behaviours due to properties such as architectured kinematics, compliance, natural resonance, damping and friction" [10].

The ultimate goal is to identify these elements in nature, both the abstract concepts and means of utilization, and to transfer similar level of perception and intelligence to man-made agents for intelligent autonomous operation in real world. More specifically, an agent that benefits from embodied intelligence for survival in a natural environment. Such bodies can be pre-designed, initiate in a general state to adapt to the task and environment, or even grow to a final robust shape while adapting to their environment, as for the living creatures. These are in contrast with the traditional robotics that the robot embodiment and natural behaviour are part of the problem to be overcome by high energy actuation and computationally expensive control units [10].

Research communities are the core to such progress and the great importance of EI has been well captured by the emerging research field of *Soft Robotics* (SoRo). In this chapter, we focus on the importance of setting "*community goals*", such as EI, MC, and SoRo. Such a community goal can put together researchers from different fields, generations, and geological regions, that are enormously important in our rapidly progressing world.

To this end, we present an overview of the research collaborations in the EI and MC communities based on co-authorship between these researchers in publications with these keywords. Then, we elaborate on one of the most important coordinated efforts to grow these research fields, the formation of IEEE Robotics and Automation Society (RAS) Technical Committee (TC) on Soft Robotics, and its achievements. Finally, a collection of ideas and opinions, some have never appeared in a publication before, are presented based on about 200 interviews with key researchers in the Soft Robotics community. We conclude this chapter by reflecting on opportunities and ideas for further collaborations in the community.

2. Communities & Collaborations: A Brainstorm Map

It is reasonable to assume that the research communities around EI and MC topics are highly inter-connected, given the similarities of concepts, their goals, and current target application.

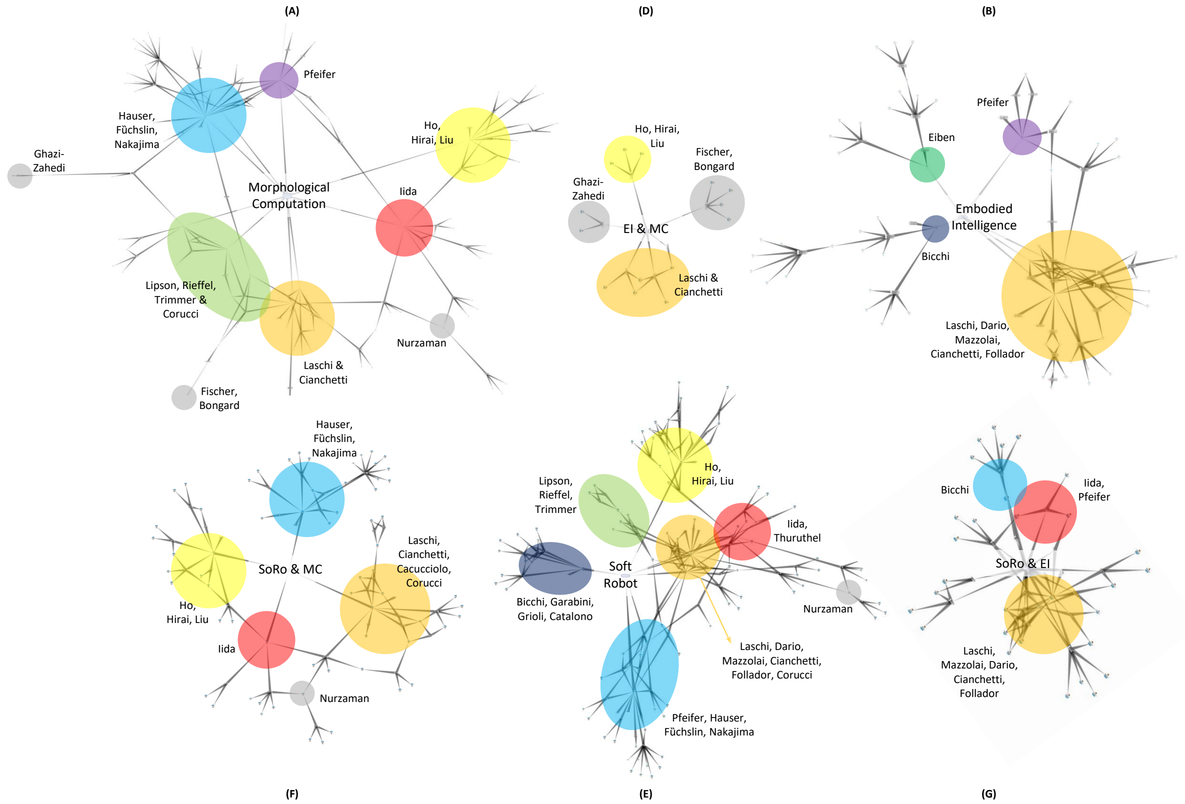

Figure 1. Brainstorm map of the researchers and their collaborations in publications with the keywords MC (A), EI (B), and both MC & EI (C) in the manuscripts' title, abstract, and list of keywords. Nodes are either researchers or publications linking the collaborators. The documents are extracted by searching the exact keywords in *www.scopus.com*. The same set of manuscripts are analysed based on SoRo (D), both SoRo & MC (E), and both SoRo & EI (F) keywords to highlight the contributions from Soft Robotics community to EI and MC research. The analysis and brainstorm map are done by *Qiqqa* software. The plots are ordered in a way that makes the comparison between the main topics and overlapping research easier.

However, that is not exactly the case. We conducted a statistical survey to better understand the collaborations formed around these topics.

A quick search of the exact terms, *Embodied Intelligence* and *Morphological Computation*, in the title, abstract, and keywords fields of accessible manuscripts through *www.scopous.com* results in 123 publications related to MC and 90 publications related to EI. The 36% higher number of publications referring to MC shows the rapid growth of the research around the topic compared to its slightly older companion topic, EI. MC owes it to its grasp within the Soft Robotics community and the communities rapid growth over the past decade. The list of top five highly cited authors are different between the two with only 6 publications with reference to both the terms in our search. hence, it is fair to refer to two to some extent distinct communities around the EI and MC topics. The more frequent appearance of the term *Artificial Intelligence* in combination with EI (28 manuscripts) and MC (14 manuscripts) terms shows wider acceptance in the two the communities.

We used Qiqqa software to analyse the collaborations inside and between the two communities based on the manuscripts' co-authorship. Fig. 1 shows the brainstorm map of the relevant publications to each topic (central node). The peripheral nodes are either the researchers or

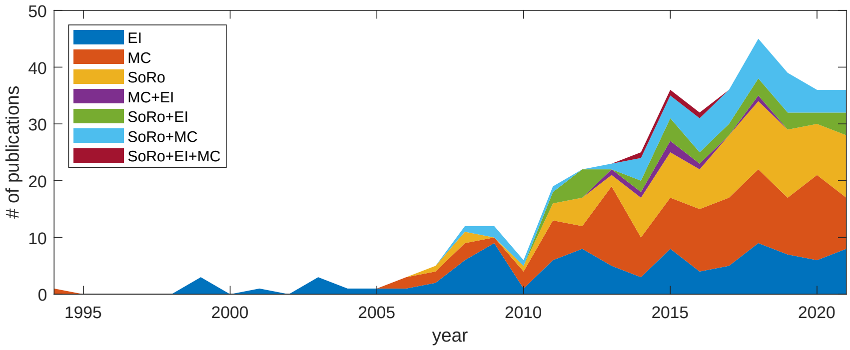

Figure 2. Histogram of the number of manuscripts containing each keyword or their combination in 1994-October 2021.

their manuscripts bridging them to the other researchers. The more interconnected nodes show the larger collaborations and closer partnerships between the researchers. The authors with five or more publications are directly connected to the central node as the most influential researchers in each group of interconnected nodes.

Fig. 1-A presents the manuscripts referring to *Morphological Computation*. Apart from R. Pfeifer who is one of the funding fathers of the field, five other main (coloured) and two emerging (grey) groups of researchers can be identified. The Wide reach of collaborations around F. Iida and the highly interconnected partnerships between the research teams in Italy (C. Laschi and M. Cianchetti) and in United States (H. Lipson, J. Rieffel, and B. Trimmer) are the highlights of this graph. It is worth mentioning that this is a map the interconnected part of the community. There are isolated research groups with multiple relevant publications that are not depicted here, for example the teams around T. Nanayakkara, J. Dambre, A. Bicchi, M. Garabini, L. Magnani, G. Dodig-Crnkovic, A. Adamatzky, K. Hosoda, P. Manoonpong, V. Muller, and P. Oudeyer.

Fig. 1-B presents a less inter-connected community around the EI topic. Four research groups are identifiable, two of which (A. Eiben and A. Bicchi) are not connected to the rest of the community. R. Pfeifer is a dominant figure in the EI community too. A strong research community is present in Italy and Switzerland. Despite the MC community, the EI community shows less activity in Asia and America.

Fig. 1-C analyses the 6 publications with reference to both the keywords in our search. The groups around C. Laschi and M. Cianchetti is the dominant figure in bringing the two concepts together, while most of the other main research researchers in the both communities (e.g. R. Pfeifer) avoided referring to both the topics simultaneously , However, a reference to both the terms is more common among the emerging nodes in the MC community (K. Ghazi-zahedi, J. Bongard, and M. Fischer).

A closer look at the contributions by the Soft Robotics community to these concepts helps with identifying the transitions from EI and MC to Soft Robotics, and how the trends have shifted from one concept after another. Fig. 1-D-F presents the interconnected part of the brainstorm map for the SoRo sub-community of MC and EI research (referenced in 91 manuscripts) and its overlap with EI (29 manuscripts) and MC (48 manuscripts) keywords. The SoRo map is more inter-connected and diverse with a strong foundation in Italian research centers. The overlap maps are very similar to the maps for MC and EI. There are only three not very recent manuscripts (2014-16) with reference to all the three keywords mostly by C. Laschi, M. Cianchetti, and V. Cacucciolo that may indicate the diverse interest of the new emerging Soft Robotics research teams when it comes to choosing between MC and EI concepts.

Finally, Fig. 2 presents a histogram for the number of manuscripts containing each keyword or their combination since the first publication on MC in 1994 by K. kamejima et al. [12] till Oct 2021. Apart from the early works in the computer science community [12], MC is a more recent concept which experienced faster growth since 2010. The correlation between the growth in MC, SoRo, and SoRo+MC compared to SoRo+EI shows the significant role of the Soft Robotics community in this growth. As mentioned earlier, there have been some efforts to reflect on the similarity of these concepts by referring to all the three terms (SoRo+EI+MC) in 2014-16. This chapter is a similar effort after 5 years to further promote such collaborations.

Once more, it is worth mentioning that these plots are based on the quick searches of the exact terms with a limited scope to a manuscript title, abstract, and keywords. Furthermore, our analysis only covers the SoRo sub-category of our EI and MC database, and does not reflect on the entire Soft Robotics community. The graphs would take a different shape if the entire content of a manuscript was analysed for similar terms (e.g. *Physical Intelligence*) around the EI and MC concepts. As a result, the provided analysis may not perfectly reflect the real impact and nature of the collaborations within and between the communities, but serves as a source of inspiration for promoting such collaborations.

3. Coordination Efforts: The IEEE RAS Soft Robotics Technical Committee

Embodied intelligence is fundamental for robotics research, and its great importance has been considered in an emerging field of robotics known as soft robotics. One of the most important coordinated efforts to grow the field is probably the formation of IEEE Robotics and Automation Society (RAS) Technical Committee (TC) on Soft Robotics, which was established in October 2012. Starting with approximately fifty members registered in its communication channel, the TC already had almost a thousand members in 2020. In order to push soft robotics field forward, since May 2013, the TC has been consistently published bimonthly newsletters to highlight scientific journal articles, important news and relevant popular articles on its official website (softrobotics.org/newsletters/), with its 48th edition published in March 2021. Due to the significantly increasing numbers of articles, the newsletter started to be published trimonthly in the 49th edition (April – June 2021 edition). The newsletter covers topics such as soft grasping and manipulation, soft locomotion, soft sensing, soft actuators, soft robot fabrication, embodied intelligence, and stretchable electronics. Up until the 49th edition, the newsletter has featured 1044 scientific articles and 387 popular articles related to soft robotics, excluding a large number of featured videos and news like conference announcement or even relevant vacancies. In 2013, the newsletter featured 64 scientific and six popular articles, while in 2020 it featured 189 scientific and 49 popular articles, demonstrating a significant increase of community size and the popularity of the field. Aside from the increasing number of feature articles, there are other interesting statistics that we can also glean from the newsletters. The first is the increasing number of 'categories' that are used to group the articles. In the first edition, for example, the scientific articles could be easily grouped into categories like sensing, actuation or manipulation. Along with the growth of the community, the featured articles become more diverse and therefore new categories like learning, modelling, control and state estimation were introduced. Another interesting statistic is the significant increase of the number of popular new articles. In the first year of the newsletter publication in 2013, there were merely six featured popular articles. In 2020, the newsletter featured 49 popular articles. As there were six editions of the bimonthly newsletter each year, it means an average of more than eight article per edition, exceeding the number of popular articles featured in the whole year of first year of the newsletter publication in 2013. Embodied intelligence is probably even more fundamentals than soft robotics itself but certainly there must be some lessons that can be taken from the growth of the soft robotics community. It is probably fair enough to say that the community cannot have such significant growth without the coordination provided by the IEEE TC on Soft Robotics, with the soft

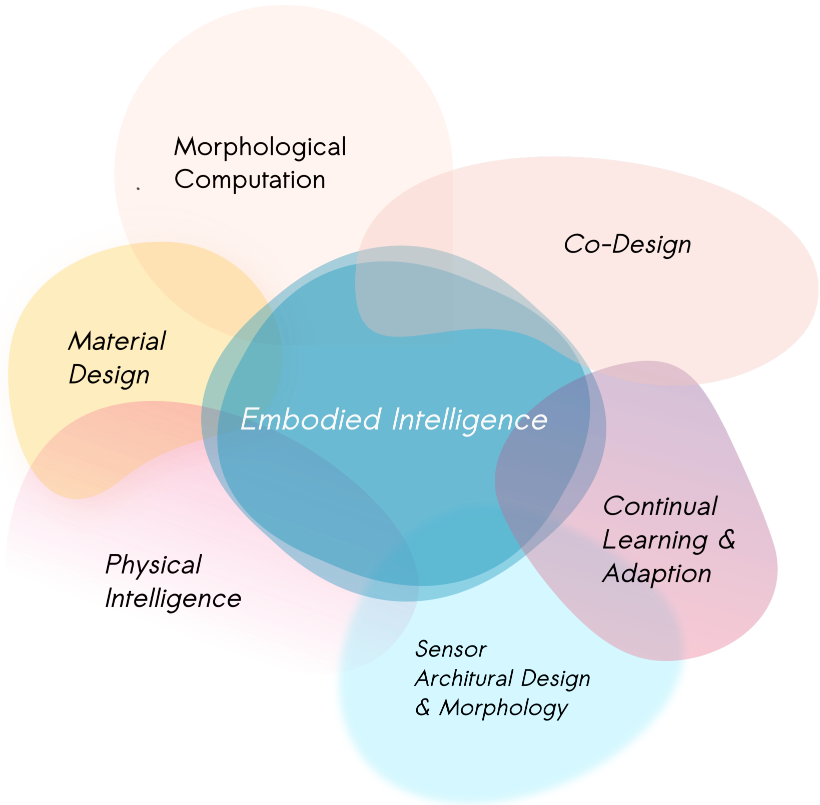

Figure 3. Key aspects of Embodied Intelligence.

robotics newsletter as one of the main driving factors.

4. Ideas & Perspectives: Reflecting on 200 Interviews

The most intriguing ideas and ground-breaking perspectives in a research field are the consequences of asking key questions. Questions such as, what is the limit of soft robots for embodied intelligence? Can soft robots be designed to adapt to environmental uncertainty e.g damage? In evolutionary terms, diverse creatures are evolved to adapt to their environment, and it seems impossible to evolve everything that could reduce fitness, which explains why humans do not have feathers.

How evolution can come up with these designs and put these materials together? There is a harmonic interplay between the brain, body, and environment. This interplay is not settled yet for example which one is more significant and whether intelligence can be manifested in the body without having a brain? Looking back to evolution, It seems the body-mind problem "embodied intelligence" according to Fumiya Iida is a hard question and a debate that is still not settled. It is mystical that humans start as sperm and evolve to the structure we have as a human. There is another deeper aspect that we still struggle to understand, what are soul, gut feelings, and intuition? All these concepts are mystical. According to Gusz Eiben "It is magical going from no-life to life, from no-intelligence to intelligence.

The question is do we need to figure out that in soft robotics? Short answer, maybe and maybe, not all creatures have a brain, for example, plants exhibit intelligence through their bodies which have known physical intelligence. Since soft robotics is based on soft materials, what kind of materials should be pushed forward to exhibit embodied intelligence? e.g. physical intelligence, effective sensing.

That leads us to the question: what is missing for an effective soft robot design? Is that developing new materials? Do we need this level of intelligence? According to Herbert Shea's thoughts regarding this point " What does it take for an artificial octopus tentacle to solve Rubik cubes, it would take several aspects that we do not master yet, like huge and efficient interaction among embedded sensing capabilities, actuating high forces to twist the Rubik's cube, local computation at tentacles tips, and main central controller to control the preferred tentacles and more unveiled question that we do not yet understand". How we can bring all these together is still challenging and it could happen when we have a defined and deep understanding of soft systems".

To understand the interplay between the brain and body in soft robotics, according to Jennifer Mather, there is the beautiful and mysterious interplay between the Octopus brain and its body "The octopus has eight flexible arms, with a huge neurological loads coordination which is necessary, Octopus are not conscious about the details of their arm, but it is believed that each arm has mini-brains which is considered lower-level subroutine. Interestingly, the octopus model is quite different from humans, we have a highly centralized controller, in contrast, they have a more distributed controller"

Designing soft robots that can adapt to damage is crucial. An interesting example, what happens if the octopus loses one of its arms, how the controller is re-distributed? it is believed that the arms are equally potentially, each arm can do what the other arm does, but even being equally potentially they tend to be not equal, they use four arms for walking, the other four arms for exploring. We do not know about the control in the arms. Another interesting engineering aspect is octopus gait analysis which could be inspiring for soft robots design. For example, human has left, right, for the horse even more interesting, but for octopus is more sophisticated gait analysis, what are the specific gait rules, which arms they should use, it is hard to imagine, which arm come first or next, but how they organize to walk, we do not know, that could be interesting to use soft robots locomotion design to explain how octopus gait analysis work.

Another important aspect of soft robotics is sensing design and how it can be embodied in soft bodies. A fascinating example from evolution is the eagle, which is considered to have an embodied sensing with low dimensional control space, according to Steven Brunton "the eagle is such a good example of a system that expertly interacting with very complicated fields and reflecting on that, there are many things are missing when it comes to robots design". The eagle and other biological systems have incredible embodied sensing, they have feathers, and inertial guidance that goes far beyond anything we build to sense their environment efficiently. Interestingly, the decision made by an eagle to hunt, fly, and avoid obstacles is based on low-dimensional control space. It does not care about billions of degrees of freedom, certain patterns matter that could be characterized and exploited. That leads us to the question of how we can leverage physical intelligence with minimal control in soft robots design which still needs more exploration.

Fig. 3 summarizes the more frequent referred to aspects of EI in our interviews. What could be still missing in soft robotics is how to co-design. According to Oliver Brock" how we can bring two paradigms: digital computation (e.g Turing machines, optimization) and morphological computation together to achieve clever designs?" Co-design is still not well established for complex problems e.g. how we bring different classes of materials to achieve interesting functionalities like toughness or leveraging physical intelligence with minimal control. An initial step towards cracking how to co-design is intuitive design with the ultimate goal of an adaptive morphology by growth. The way of how to co-design would be a new chapter in robotics

5. Conclusion

Biological examples show that adaptations spanning across neural and physical structures are important for realtime actions to maximise rewards. *Embodied intelligence*, *Physical intelligence*, *Morphological Computation*, and *Soft Robotics* concepts have paved the road toward identifying the abstract forms behind such adaptations. In this chapter, we highlighted the importance of setting such community goals in establishing a diverse and inclusive interdisciplinary research environment, which are extremely important in the rapidly progressing world that we live in.

6. Acknowledgment

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