The extended phenotype in robots: A new perspective and challenges

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Abstract— **The paper introduces a new perspective to robotics research by borrowing a concept from evolutionary biology, i.e. the extended phenotype. We argue that alternative technologies can enable robots to extend their task handling capabilities through the extended phenotype. We show that how unconventional material may play an important role in the technologies. Finally we discuss challenges raised by the perspective.**

I. INTRODUCTION

The paper is not about a theory, or a research method, or a specific technique. It introduces a new perspective into robotics research: Robots, which are created by human beings for various tasks, may autonomously extend their task handling capabilities through the extended phenotype (EP), a revolutionary concept proposed 30 years ago by the evolutionary biologist Richard Dawkins [1]. We expect this perspective will inspire alternative robotics technologies, where unconventional material plays an important role.

A. The Extended Phenotype

In biology, the concept of EP originated from the gene-centred view of evolution. It considers the conventional phenotype as a special case in which genetic effects are confined to the individual body in which a gene sits. EP includes all effects of the gene upon the world (p. 286 in [1]). Those effects could be in the form of animal artefacts or host phenotypes of parasite genes, as exemplified by Dawkins in his book. It is important to note that only those that influence the survival chances of the gene, positively or negatively, can be treated as extended phenotypes (EPs) [1], [2]. As a result of evolution, EPs such as spider webs, bird nests, and beaver dams represent how those animals adapt to the environment so far to increase the survival chances of genes.

A similar concept can be established in robotics, such that a robot may either construct its own artefacts or exploit existing objects (living or not) as EPs (see Fig. 1). EPs in robotics should be similarly limited to those that influence task handling, positively and negatively, from the robot's own point of view. For example, robotic artefacts from automated fabrication or construction [3] may only be considered as EPs if they influence the robot's task handling capabilities. A robot may have many EPs depending on given tasks. EPs that have a positive influence on task handling may either be pre-determined through programming the behaviour of a robot, or in a stochastic or evolutionary manner, emerge from a pool of EPs according to dynamical task-environment.

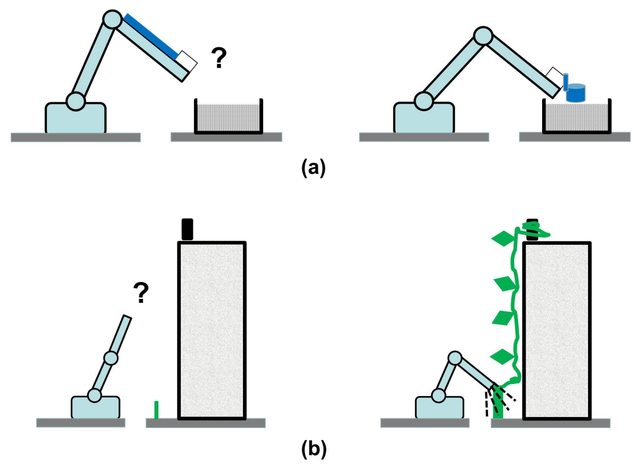

Fig. 1. Robots with EPs are able to extend their task handling capabilities. (a) An example where a robot (arm) makes an artefact of a scoop (in blue) for getting liquid from a container. (b) Another example where the robot exploits a living plant (in green) to reach a target (in black) beyond the initial reaching range of the robot.

B. A Comparison with Self-X Technologies

Since the purpose of introducing EP into robotics is to inspire alternative technologies to enable robots to extend task handling capabilities, it is useful to review previous technologies with similar aims. These technologies follow various concepts of so called robotic self-X [4], which mainly refer to self-reconfiguration and self-assembly. Similar to EP, self-X stresses the importance of a robot's own point of view. The technologies emphasize the necessity of predefined robotic modules, which can be controlled to achieve different connectivity patterns (therefore morphologies) for functions beyond the capability of individual modules. Some of the problems faced by the technologies include cost, reliability, and the number of achievable and functional morphologies, etc [5], which are all rooted in the desire for modules. In contrast, technologies following the concept of EP could be more efficient in task handling. A robot can make artefacts or exploit existing objects with a low cost and a high morpho-functionality. When a change presents in task-environment, the robot can flexibly dispose the old EP and make a new one. The higher flexibility and lower cost could be the potential advantage of the technologies inspired by EP.

II. MATERIAL CONSIDERATIONS

EPs in biology may help animals where genes sit for different purposes, and those purposes determine the choices

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of material to form EPs. For example, protein silk is used by both spiders and caddis-flies to construct webs or nets for catching food; rigid material such as stones and wood is used by caddis-flies and birds to build houses or nests to protect and grow offspring; and living ants and caterpillars are exploited as hosts by some nematodes or viruses to help disperse eggs or infective particles, etc.

The choice of material for EPs in robotics should be also subject to the way a robot extends its task handling capabilities. Some of the aspects that a robot may extend include passive structures, actuation, sensing capabilities, and computational abilities, etc. These aspects have different requirements for material properties in order to enable EPs to influence the robot's behaviour. At the same time, the robot needs to understand properties of the material, so that it knows how to make artefacts or exploit natural dynamics.

Below we list some material properties that we think human engineers need to consider when building robots that are capable of forming EPs:

- Strength and modulus. They are among the most common mechanical properties that determine what structures are capable of doing. They are important for a robot to extend passive structures for e.g. loading or elongation, as well as for mechanical parts in actuation and mechanosensing.
- Phase transitions. In some occasions where variations of structural strength or stiffness are needed, material that can change between phases could be helpful. Bi-directional and repeatable phase transitions may be induced thermally or otherwise.
- Plasticity. It is important for the robot to control the on-line fabrication process for artefacts. Some parameters such as viscosity and yield strength could be altered by controlling temperature for the robot to form EPs.
- Adhesion. This property will be discussed as a challenge in the context of connection and disconnection in greater detail in Section IV.B.
- Electrical conductivity. It is necessary for the robot to construct active artefacts, especially as sensors and computational units.
- Living objects. Exploitation of living objects by a robot may simplify the problem as compared to making artefacts. As an example shown in Fig. 1b, with a simple local action of watering a plant, a robot may be able to grow it for extending reaching range for grasping. It is however important to distinguish a robot using living objects itself from human designing and controlling robots with living objects.

III. A CASE STUDY

To give a more concrete idea of the kind of technologies potentially with the concept of EP, we show a case study which corresponds to the example in Fig. 1a. We present the robotic system and explain the role the material plays.

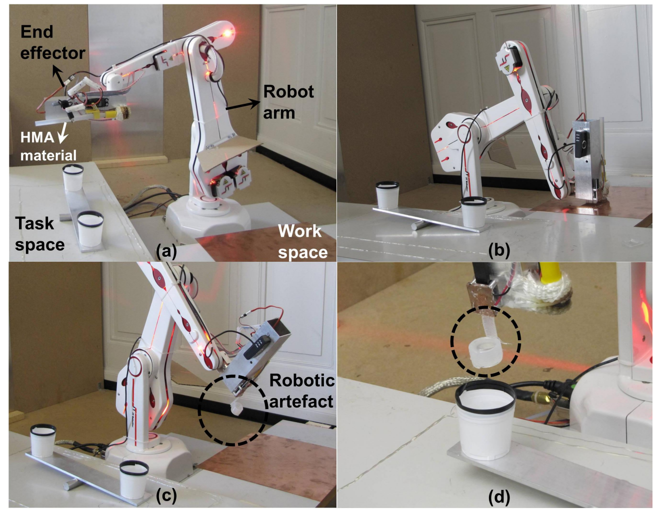

Fig. 2. A case study of a task exemplified as in Fig. 1a. (a) A robot identifies task requirements. (b) The robot makes a scoop artefact as EP. (c) EP is shown in a dashed circle. (d) The robot uses the scoop to get water from one container to the other. The material used by the robot to make the artefact is thermoplastic adhesive. Photo courtesy L. Brodbeck.

A. System and Material

we have developed a robot manipulator platform which consists of a special end effector mounted on a commercial robot arm, as shown in Fig. 2a. The 5-axis robot arm (500 mm reaching distance, 1 kg maximal payload, R12 firefly, ST robotics, UK) is fixated on a flat open ground, where one table serves as a work space for making robotic artefacts, and a second table serves as the task space. There is a balance sitting in the task space, and the robot needs to get water from one container at one end of the balance and transport it to the other. By repeating this, it is expected that the balancing condition will eventually change. However, the end effector does not originally have the function for getting liquid. It has material handling devices that can make robotic artefacts on-the-fly from on-board material.

The material used by the robot is thermoplastic and adhesive, called hot melt adhesives (HMAs). The type of HMA used here (Pattex Hot Stick Transparent, Henkel, Germany) is based on copolymer ethylene vinyl acetate and provided in cylindrical sticks. The HMA is solid at room temperature with storage modulus and tensile strength both over 10 MPa. It gets softened at 80-90°C, and has a melting temperature at 170-200°C. Above 55°C it gets adhesive and may from bonds with any solid surfaces upon cooling with a bonding strength of as high as 1 MPa. The phase transition is bi-directional and repeatable. HMAs in general have been proven easy-to-control and economic in industries such as packaging, furniture, book binding, and aerospace applications, etc.

B. Processes

In this case study, we focus on showing how EP can extend the robot's task handling capabilities, thus neglect the evolutionary process but pre-define the artefact and pre-programme processes how the robot may make the artefact for completing a task. Fig. 2 demonstrates a typical sequence of processes. The robot first identifies the task requirement and water container's dimension with some on-board sensors (not shown here). It then determines the dimension of the artefact and makes one on-the-fly in the work space. One of the simple fabrication methods is Fused Filament Fabrication (FFF), where the robot can exploit the viscosity of the HMA at higher temperatures and deposit filaments to form structures with arm-controlled trajectories. When the HMA was melted at 150°C, the deposition speed could be controlled at 2.5 mg/s. It took the robot about 40 minutes to fabricate a scoop artefact with an opening diameter of 30 mm and a height of 20 mm. Without considering the power needed by the robot arm to move, power consumption involved in making an artefact of such a dimension was around 15 W. The robot subsequently forms a connection with the artefact, and finally uses it to complete a previously impossible task.

IV. DISCUSSION ON CHALLENGES

In this section, we discuss some of the challenges that we think will be faced by future technologies inspired by EP.

A. *Morphological Computation*

The first challenge is to develop a novel way of robot control, which involves identifying the role robotic EPs play in morphological computation [6]. In Dawkins' book, this issue was not explicitly discussed. One reason could be that here-and-now interactions between EPs and environments, as direct drives for morphological computation, are treated as an ecological factor that influences an animal's behaviour, rather than an evolutionary factor to influence the survival chance of a gene. For example, the same spider may abandon old webs and make different new ones subject to geological changes. This type of 'adaptation' is closely related to properties of the material used for EPs.

B. *Connection and Disconnection*

The second challenge is about connection and disconnection between EPs and conventional phenotypes or genes, whichever the robot who makes EPs is considered as. This includes both physical or mechanical (dis)connection and electrical (dis)connection, and it has to be automatically done by the robot. No matter what aspects of robotic EPs try to extend, they involve transmission of force or information. Based on the present technological level, it is beyond a robot's ability to use field effects for non-contacting transmission. Therefore, contacting mechanisms are vital for a robot to make use of either its artefacts or existing objects. Traditional connection mechanisms were mainly for designs by human beings, and they might fail to meet the need of the robot facing complex-shaped artefacts. Intrinsic adhesion properties of material could be a solution [7], and we expect an increasing number of technologies to emerge along this line. Disconnection control is usually neglected in robotics research. However it is important when a robot needs to flexibly change EPs for different tasks and environments.

C. *Trade-offs in Material Properties*

The last challenge we would like to discuss here is closely linked to material. As introduced in Section II, unconventional material will play a central role for technologies following the concept of EP, mainly in the sense that properties can be exploited by the robot to gain advantage during task handling and interactions with the environment. However, we should be aware that there is no mighty material which could have all the properties a robot wants. For example, there is an inverse correlation between modulus and adhesion [8], which means it is difficult to have rigid material with a good bonding strength. Another example is that viscosity increases with electrical conductivity in the case where electrically conductive compounds are added into e.g. polymer [9]. That will lead to the requirement for a larger force by the robot to make artefacts out of the material in a similar way to FFF. These trade-offs in material properties must be taken into consideration when developing technologies to enable a robot with EPs.

V. CONCLUSION

We introduced a new perspective to robotics research, i.e. a robot may make artefacts or exploit existing objects to extend its task handling capabilities or increase adaptability to dynamical environments. We suggested that the use of unconventional material shall play an important role in technologies following the concept of EP, and specified some material properties and their potential benefit to EPs. We grounded the new perspective with a solid case study, where a robot made a scoop artefact from hot melt adhesive and used it for a water transportation task. we further discussed three challenges faced by future technologies.

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