INTELLIGENT ROBOTS: THE QUESTION OF EMBODIMENT

Brian R. Duffy, Gina Joue
Department of Computer Science, University College Dublin, Ireland
Brian.Duffy@ucd.ie, Gina.Joue@ucd.ie
http://dead.ucd.ie/Welcome.html

Abstract – *Embodiment has been perceived by some as one of the fundamental issues in the pursuit of artificial intelligence, a perspective that has only been mainstream in recent years. This paper discusses embodiment, its interpretations, misinterpretations and the role it has played in artificial intelligence to date and specifically in the realisation of the "intelligent robot". While some believe that simply placing a controller in a physical environment constitutes a sufficient degree of embodiment, we wish to emphasise that agent-world interaction must develop away from this "ON-World" approach and seek to concentrate on "IN-World" interaction, participation, and adaptation.*

1 INTRODUCTION

Over the last decade there has been significant development in the Artificial Intelligence research community regarding the concept of embodiment and the development of an artificially intelligent robot. Two distinct methodologies have emerged regarding *representation* vs. *perception*. Traditionally, artificial intelligence has developed from the representational perspective based on world modelling with a change in the late 1980s to work on perception in an attempt to combat failings of representational methods. Section 2 briefly outlines the evolution of AI research from classical symbol manipulation algorithms to embodied Artificial Life experiments with autonomous mobile robots. This is followed by a discussion of the existing approaches and their interpretation regarding embodiment in robotics research. Section 4 seeks to discuss the fundamental issues towards a more complete understanding of embodiment and leads to the proposed IN-World vs. ON-World differentiation between *weak* and *strong* embodiment.

It is important to note that "embodiment" refers strictly to the physical existence of a body. While the term is used frequently to refer to the association of certain attributes to a virtual agent, i.e. in the form of some visual avatar and observable behavioural characteristics, this work stipulates that such interpretations of "embodiment" are simply visual aids for software algorithms and do not constitute embodiment.

2 ARTIFICIAL INTELLIGENCE

Artificial intelligence was initially interpreted as that which attempts to prove the *Physical-Symbol System Hypothesis:*

> *Formal symbol manipulation is both a necessary and sufficient mechanism for general intelligent behaviour. (Allen Newell & Herbert Simon 1957* [1]*)*

Simon maintained that the human cognitive system is basically a serial device. Efforts to solve the AI problem that follow this hypothesis are now termed the *classical AI* approach.

When interpretation of the results is via the medium of a human, classical AI provides a rich source of control ideas. Problems arose when these control paradigms were applied to robotics, and in particular the control of autonomous mobile robots with little or no user intervention. The original theory that robots would simply provide the sensors and actuators for an artificial brain became seriously flawed. Problems arose with real-time performance and stability through, for example sensor noise, and maintaining representational model validity. The well-known example of these problems is the robot “Shakey” [2]. More elaborate models resulted in increasing computational effort that often proved too cumbersome and slow for real-world applications.

The inability of current “classical” AI systems to handle unconstrained interaction with the real world has recently lead to a search for new control architectures for autonomous agents. It became apparent that understanding *system-environment* interaction was fundamental towards achieving robust control for autonomous robots existing in a physical world. This lead to a series of provocative papers by Rodney Brooks [3] [4] [5] arguing that real world autonomous systems or embodied systems must be studied in dealing with the problems posed by classical approaches. Issues in real-time processing became very “real” whereby if the robot could not cope, it crashed into something. Only by direct interaction could a robot gain an environmental “understanding”. Recent research into embodiment, sociality and emotions are now approaching the problem from an even comprehensive perspective [6] [7] [8] [9].

The following sections provide an insight into the fundamental stages in the evolution of artificial intelligence from symbolic computation systems to the modern embodied cognition approaches.

2.1 Symbolic Computational Systems

The thesis of *Good Old Fashioned Artificial Intelligence* (GOFAI) is that the processes underlying intelligence are symbolic in nature. A Turing model [10] of intelligent behaviour, viewed as essentially computational, inspired these first steps into the development of “artificial intelligence”. More specifically, GOFAI models human intelligence as von Neumann computational architectures that perform computations on abstract symbolic representations. These computations are governed by a stored program, which contains an explicit list of instructions or rules. These rules transform the symbolic representations into new symbolic states. As such, GOFAI depicts mentality within the context of what philosophers know as the *Representational Theory of Mind* (see [11] for a recent discussion), according to which the mind is an entity that performs calculations on mental representations or symbols, which refer to features of the outer world.

2.2 Computational-Representational Understanding of Mind

Thagard defines a central hypothesis of cognitive science, the Computational-Representational Understanding of Mind (CRUM):

> *“Thinking can best be understood in terms of representational structures in the mind and computational procedures that operate on those structures.” (Thagard* [12]*)*

While there is much speculation regarding the validity of this statement, he continues by stating that the central hypothesis is general enough to encompass the current theories in cognitive science including connectionism.

While this hypothesis is strictly scientific, it does not take the current expansion of the cognitive science umbrella to encompass embodiment, albeit either physical or social. The principle drawback of the classical approaches to artificial intelligence as a control paradigm for robots is that explicit reasoning about the effects of low-level actions are too computationally expensive and time consuming to generate real-time behaviour. Another is the perception complexity problem, where noise and errors in the perceived environment result in decisions based on incorrect perceptions. As the environment itself increases in complexity, its correct perception becomes even more difficult.

2.3 The Real World and New Artificial Intelligence

The fundamental difference between the *representation* (or “Classic AI”) and *perception* (or “New AI”) based approaches lies in the degree of interaction between the “body” and the “brain”. While two communities battle over the validity of seeking more exact world representations, intuition leads many of us to the conclusion that approaching the problem of robot control by merely trying to increase the accuracy of strictly structured, exacting, and continuous quantifications, is not the only possibility. This may only provide a digital solution to an analogue problem, and consequently suffers from ever increasing complexity. Physical embodiment *necessitates* the use of approximate solutions as such solutions are inherently based on noisy and often incorrect perceptions. As yet, the relationship between body and intelligence continues to create a lot of debate and food for thought with few claiming that there is no relationship between the two [3] [8] [13] [14] [15] [16]. Embodiment constitutes system-environment interaction and is discussed in greater detail in section 3 and 4.

Other than the aspect of being very computationally demanding, exact solutions also may not even be valid to the reality of the application of the solution as they are quickly outdated in complex dynamic environments. A simple example of this would be a mobile robot undertaking a docking procedure for recharging. Odometric errors and the robot's inability to drive exact and correct paths demonstrate where an exact path plan is both unnecessary and unachievable. It is analogous to the notion of trying to realise a straight line in reality that can *only* exist in theory. This exemplifies the differences (and problems) that exist between *representation*- and *perception*-based methodologies.

The term *New Artificial Intelligence* is a recently coined term and has been used by researchers like Pfeifer *et al.* [8] in discussing embodied cognitive systems and in particular mobile robots. *New AI* is a new methodology for studying intelligence and for understanding the mind with a view to providing a framework for alternative approaches to the classical stance. One of the main characteristics of *New AI* is its investigation of system-environment interaction. Although neuroscience, and in particular the field of neural information processing, has a bias towards information processing, it is becoming ever more obvious that there are two dynamics, namely the control architecture, and the environment. When integrated properly, there can be cooperation between the two, which could result in control architectures utilising certain environmental properties to their benefit. A robot's control architecture determines how behaviour is generated based on signals from sensors and to motor systems. Research in *bottom-up* approaches via reactive architectures has primarily lead to *emergent behaviour* [17] [18] [19] [20]. Such approaches involve quite simplistic control architectures and highlight how relatively complex behaviours, for example the flocking behaviour in [21], do not need complex control structures. . Researchers working within this paradigm have not hesitated to term such emergent behaviour's as "intelligent". While it can be extremely difficult to reproduce such behaviours explicitly, the paradigm does not facilitate the development of explicit complex behaviours. While interesting, inherent problems regarding recordability, observability, repeatability, and analysis (both quantitative and qualitative) challenge this approach from a scientific perspective. In contrast, research on *top-down* control via deliberative architectures has displayed high-level reasoning capabilities but lacks real world robustness.

The inherent problems with existing robot control approaches therefore reinforces the importance of understanding embodiment.

3 EMBODIMENT IN ROBOTICS: A BRIEF REVIEW

René Descartes is referred to as the father of cybernetics due to his study of the human body as a machine. Descartes, in *Meditations* [22], aimed to show that mind is distinct from body. He points out that even though he may have a body, his true identity is that of a thinking thing alone and, indeed, his mind could exist without his body. He argues that humans are spirits, which occupy a mechanical body, and that the essential attributes of humans are exclusively attributes of the spirit (such as thinking, willing and conceiving), which do not involve the body at all. Sense perception, movement, and appetite may require a body but they are only attributes of our body and not of our spirit and, hence, do not comprise our essence.

While some treat the body as peripheral and tangential to intelligence, others argue that embodiment and intelligence are inextricably linked [3] [14]. In contrast to the representational CRUM perspective, Brooks popularised the claim by the German philosopher Heidegger [23] that we function in the world simply by being part of it. Brooks uses the phrase "being-in-the-world" in terms of his implementation of the subsumption architecture to autonomous mobile robots. Experience in building robots has led Brooks to argue that embodiment is vital to the development of artificial intelligence [5] [24]. Brooks advocates the behaviourist approach to combat the difficulty in developing purely internal symbolic representational models of reality utilised in classical AI approaches.

Lakoff *et al.* argue that our ability to understand and reason abstractly relies heavily on our bodily experience and that "high level" intelligence depends crucially on embodiment [15] [25]. Based on the argument of movement, manipulation and perception involving the use of recurring patterns, this promotes the concept of linking embodiment to intelligence. Phenomenologists also argue against the use of internal symbolic representations or mental states saying that *"an embodied agent can dwell in the world in such a way as to avoid the…task of formalising everything"* because its *"body enables [it] to by-pass this formal analysis"* [16]. Dreyfus also says that when people have "*mental considerations*", they "*do so against a background of involved activity*" [23].

Clark uses the term "blueprints", indicating a highly detailed plan or specification, in discussing cognition and specifically "embodied cognition" in relation to the developmental process in infants, according to which "*mind, body and world act as equal partners*" [13]. Clark follows the notion that embodiment is crucial to intelligent systems, which research has traditionally tended to dissect.

Embodied cognition is unique for all natural systems. This is due to the individual experiences collected during a system's lifetime. It is little argued that intelligent systems are required to have some learning from experience mechanisms in order to function in complex nondeterministic environments. The system must be able to update and add to its knowledge set in order to survive. The "Artificial Life" or "Alife" community has approached the notion of a robot "surviving" from an alternative perspective (see [26] for an introduction). *Artificial Life* involves the embodiment of robots in an environment with the principle of surviving for a period of time, generally a time scale measured as a multiple of the robot's battery life (i.e. 30x battery life). Artificial life has been defined by Langton as being:

> "*The study of man-made systems that exhibit behavio[u]rs characteristic of natural living systems. It complements the traditional biological sciences concerned with the analysis of living organisms by attempting to synthesize life-like behavio[u]rs within computer and other artificial media.*" *(C. G Langton [27])*

Olson [28] discusses the notions of "weak artificial life" and "strong artificial life" by differentiating *weak alife* as being the use of computers to simulate life, and *strong alife* as the claim that "*computer programmers can, at least in principle, go beyond mere modelling and literally create living things*". Olson does not discuss the use of physical robots, but rather seeks to argue that computer-generated organisms are material objects. This is discussed from a very philosophical perspective and lacks foundation in real world concepts and applications. While some research has been conducted in simulators and purely software-based systems, the real challenge lies in physically embodied artificially "alive" entities.

4 EMBODIMENT: A MORE COMPLETE DEFINITION

While some believe that implementing a control paradigm on a physical robot is sufficient for fulfilling the embodiment criteria, Dautenhahn and Christaller [29] argue that this results in a robot not being aware of whether it is acting in a simulated or physical body. They write that the "*development of a* conception *of the body, which is generally discussed as the acquisition of a* body image *or* body schema, *is necessary for embodied action and cognition*". They continue in proposing that the use of evolvable robots with an adaptation of both body and control mechanisms to its environment could provide an ideal solution.

Maturana and Varela [30] differentiate between this issue of animal systems versus mechanical systems by concentrating on the organisation of matter in systems (see also [31]) via the terms *autopoiesis* and *allopoiesis.* In essence this constitutes the fundamental distinction between true embodiment and an artificial intelligence perspective of embodiment. *Autopoiesis* means self- (auto) – creating, –making, or –producing (poiesis). Animal systems adapt to their environment at both macro (behavioural) and micro (cellular) levels and are therefore termed autopoietic systems. Mechanical systems on the other hand can only adapt at a behavioural level and are termed allopoietic.

Similarly, Sharkey and Zeimke highlight in [31], "[l]iving systems are not the same as machines made by humans as some of the mechanistic theories would suggest". The fundamental difference lies in terms of the organisation of the components. Autopoietic systems are capable of self-reproduction. The components of a natural system can grow and ultimately grows from a single cell, or the mating of two cells. In such systems, the processes of component production specify the machine as a unity.

Allopoietic systems are, on the other hand, a concatenation of processes. Its constituent parts are produced independently of the organisation of the machine. This fundamental difference, in the context of artificial intelligence, has been highlighted in [31] where the notion of evolvable hardware is discussed. The designer of a robot is constrained by such issues as the physical and chemical properties of the materials used, by the limitations of existing design techniques and methodologies. The introduction of evolvable hardware could help overcome the inherent global limitations of the robot end product by facilitating adaptation and learning capabilities at a hardware level rather than only at a software level. This adaptability is often taken for granted in biological systems and likewise ignored when dealing with such issues as robustness, survivability, and fault tolerance in robotic systems. Sharkey and Zeimke highlight the lack of evolvable capabilities in allopoietic systems as being directly related to its autonomy, i.e. it is not. Biological or autopoietic systems *are* fully autonomous.

4.1 Embodiment in Robotics: IN-World *vs* ON-World

With regard to robotics, the embodiment question fundamentally envelops the issue of whether it is "IN-World" or "ON-World". The primary distinction between IN- and ON-World embodiment is the notion of the robot *adapting* at a macro and micro level to its environment or not. The question is whether there is a difference between the performance of a controller with actuators and preceptors (a robot ON its environment) and the behaviour of an agent being a part of its environment (a robot IN its environment). ON-World corresponds to an allopoietic interpretation of embodiment in robotics, while IN-World seeks to approximate the notion of autopoietic embodiment.

Smithers [32] supports the "ON-World" vs. "IN-World" philosophy in saying that "*the agent [is] … directly involved in bringing about the 'world' it experiences, rather than being an external observer of it able to act on it*" (as is the classical interpretation). This is a fundamentally different perspective from the main body of research being currently conducted using mobile robots. Too much emphasis is being placed on the notion of building a robot and then *placing* it in its environment. Not enough distinction has been made between the notion of the robot being "ON" its environment where it is not considered as *part of* its own environment *per se*, and the robot being "IN" its environment where it functions directly with its environment in a dynamic, adaptive and interactive way, and very much in real-time. Classical AI is synonymous with the "external observer" perspective of ON-World embodiment.

This highlights the difference between *interpretations* of embodiment and a stronger notion of embodiment. Sharkey and Zeimke [31] also distinguish between IN- and ON-World embodiment when they refer to existing robot approaches by saying that "most of the body is a container for the controller, a stand to hang the sensors on, and a box for the motors and wheels. There is no interconnectivity or cellular communication". IN-World, in contrast to ON-World, does not *require* the robot to have all possible maps and internal representations of the world in conjunction with a "complete set" of perceptor devices to perceive the world, but rather, provides it with some degree of mobility and adaptability *in order* to interact with and influence its environment. This integration of the agent *into* the environment allows greater real world autonomy; otherwise it is merely situated in its internal static representation of the real world, and as such is inherently flawed.

The ability of a system to adapt to, learn from and develop with its environment, which constitutes its interaction with its environment, is directly related to whether that system will "survive" in that environment. Embodiment should subsume this degree of functionality of the system. As highlighted in [31], "[t]he chemical, mechanical, and integrating mechanisms of living things are missing from robots”. This clarifies the fundamental distinction between “strong” embodiment and simply placing a computer with wheels in the real world.

The strong embodiment of an agent into its environment can be perceived as a more cohesive integration with the environment promoting learning and adaptation requiring the agent to have:

- the ability to coordinate its actuator and sensor modalities to interactively explore its environment,
- goal-oriented behaviour on micro and macro levels,
- bi-directional interaction between the agent and its environment,
- bi-directional communication between the agent and other agents in the environment, and
- an understanding of the physics of the environment, e.g. gravitational effects and friction, to reduce internal environment representation loading by inferences

The environment is necessarily influenced by the agent’s actions; otherwise the action is merely a mental exercise with no physical causalities. Viewing interaction as a goal-oriented task forces the agent to only concentrate on relevant features in the environment. Otherwise the system is subjected to an onslaught of inconsequential features resulting in unnecessary sensory and computational loading.

As the ON-World robot is built to completely constrain its environmental interaction by its internal system architecture, which is inherently impossible. It cannot have expectations that can only arise within a dynamic interactive scenario. The degree with which the agent can anticipate causal realities is very much restricted. The ability to be autonomous depends on whether the agent’s expectations and perception of the environment is correct. The evaluation is based on feedback as to whether the agent’s set of behaviours acts towards realising a particular goal, and actually allows achievement of the goal. This can only be in the form of a dynamical process requiring interactive learning and adaptation, resulting in the ON-World agent having difficulty reaching such explicit goals.

In seeking to understand the differentiation being proposed here, we can perceive the “ON-World” perspective as a *weak* notion of embodiment analogous to the allopoietic distinction drawn earlier and “IN-World” as a *strong* notion of embodiment and as such more autopoietic. We have argued that there is a distinction between the performance of *weak* embodiment and *strong* embodiment in robotics. Weak embodiment is the first stage in control methodology that situates a physical robot in the real world and have it function autonomously by allowing sensory input to situate the “body” in its internal map. However, this type of embodiment still only places the body in static abstractions of the world and not in the dynamic real world itself. Weak embodiment therefore characterises the research to date on the embodiment of existing artificial intelligence techniques via mobile robots, but as argued here, has not as yet achieved a cohesive and integrated system-environment interaction. Weak embodiment is simply the “hooking” of internal representations via a body to the real world.

Emergent behavioural systems [17] [18] [19] [20] have attempted to broach the inherent problems with weak embodiment in using relatively simple behavioural models based on sensory-motor actuation and simple goals analogous to that found in reflexive or reactive systems and insect colonies. This approach constitutes a step from *weak* embodiment towards a stronger more system-environment integration but, as discussed in section 2.3, fails to facilitate explicit complex behaviours and is therefore only a stage towards achieving *strong* embodiment.

Strong embodiment involves the robot being a more integrated part of the environment within which it exists. It *is* the environment as much as existing in it. The robot has to understand the world within which it is embodied. Sharkey and Zeimke [31] refer to *strong* embodiment as implying “that the robot is integrated and connected to the world in the same way as an animal”. While an apparently vague definition, the issue is to analyse exactly *how* an animal interacts with its environment and how it is also inherently constitutes an element of the environment for others. The fundamental difference between an allopoietic and autopoietic entity defines the level of possible embodiment, either strong for animals or weak for robotic entities. Based on the current technologies for the design and realisation of a robotic entity, strong embodiment analogous to the autopoietic features of animal systems is not yet available.

As proposed in [9], the development of social robots and the framework to support this may facilitate a stronger notion of embodiment than currently exists. In order to support the development of such a robot, an architecture with sufficient social and intentional functionality is required, for example [33]. The result would be of the form of a physical, socially capable robot with a concept of identity, learning and adaptation capabilities, sensor and actuator functionality and existing in a social environment [9]. The robot must be able to perceive, reason, and function completely autonomously. It should be able to form opportunistic collaborations with other robot entities to solve complex tasks efficiently and quickly when possible. Similarly, work on evolvable hardware and modular robotics seeks to extend existing behavioural adaptation techniques by addressing a robots adaptation to its environment at a physical level [34] [35].

5 CONCLUSIONS

While embodiment has been approached from different perspectives by the mentioned authors, the conclusion is similar. Embodiment is an inherent property of an agent that exhibits intelligent behaviour leading to the now established hypothesis that, in order to achieve cognitive capabilities or a degree of intelligence in an agent, a notion of embodiment is required where there is cohesive interaction between the environment and the body.

The objective of this paper has been to discuss the current interpretations of embodiment within the artificial intelligence community with a view towards focusing attention on one of the fundamental issues that constitutes our understanding of intelligence. It advocates the view of developing away from current thinking in *weak* or *allopoietic* embodiment towards a more robust notion of *strong* or *autopoietic* embodiment.

Existing and current work into the field of social intelligence and particularly social robotics seeks to develop a *stronger* notion of embodiment via the use of an intentional architecture (the *Social Robot Architecture*), social analogies such as identity, character and roles, and a high level agent communication language towards realising a robot system that exists IN its world [33] [36] [37].

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