Embodiment in Cognitive Systems: on the Mutual Dependence of Cognition & Robotics

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***Abstract*— Cognitive systems anticipate, assimilate, and adapt. They develop and learn, predict, explain, and imagine. In this chapter, we look briefly at the two principal paradigms of cognition, cognitivism and emergence, to determine what embodied form each entails, if any. We highlight one specific emergent approach to embodied cognition — enaction — and discuss the challenges it poses for the advancement of both robotics and cognition.**

***Index Terms*— Cognition, robotics, embodiment, cognitivism, emergent systems, enaction, development, autonomy.**

I. INTRODUCTION

In recent years, robotic systems have increasingly been deployed in the empirical study of cognition. In this introductory chapter, we will explore the basis for the relationship between these two areas, with the specific goal of teasing out exactly what role robotics plays in cognition research and whether or not it is a necessary role. To do this, we briefly identify the different approaches that have been taken to modelling and realizing cognitive systems and the relevance of embodiment to each approach. We then examine what it actually means to be embodied and identify different forms of embodiment. By considering the different pairings of modes of cognition and modes of embodiment, we can reveal the different roles of robotics in cognition research. We focus on one particular pairing which forms the cornerstone of enaction, a far-reaching paradigm of adaptive intelligence founded on generative (*i.e.* self-constructed) autonomous development and learning [1], [2]. Our goal here in highlighting enactive systems is not to present a comprehensive review of the field but to identify its chief tenets and anchor the important relationship between cognition and robotics in a significant research paradigm. We conclude with an overview of the challenges facing both robotics and cognitive systems in pushing forward their related research agendas.

II. COGNITION

Cognitive systems anticipate, assimilate, and adapt; they develop and they learn [3]. Cognitive systems predict future events when selecting actions, they subsequently learn from what actually happens when they do act, and thereby they modify subsequent predictions, in the process changing how things are perceived and what actions are appropriate. Typically, they operate autonomously. To do this, cognitive systems generate and use knowledge which can be deployed not just for prediction, looking forward in time, but also for explanation, looking back in time, and even for imagination, exploring counterfactual scenarios.

The hallmark of a cognitive system is that it can function effectively in circumstances that were not planned for explicitly when the system was designed. That is, it has a degree of plasticity and is resilient in the face of the unexpected [4]. This adaptive, anticipatory, autonomous viewpoint reflects the position of Freeman and Núñez who, in their book *Reclaiming Cognition* [5], assert the primacy of action, intention, and emotion in cognition. In the past, however, cognition was viewed in a very different light as a symbol-processing module of mind concerned with rational planning and reasoning. Today, however, this is changing and even proponents of these early approaches now see a much tighter relationship between perception, action, and cognition (*e.g.* see [6], [7]).

So, if cognitive systems anticipate, assimilate, and adapt; if they develop and learn, predict, explain, and imagine, the question is how do they do this? Unsurprisingly, many approaches have been taken to address this problem. Among these, however, we can discern two broad classes: the *cognitivist* approach based on symbolic information processing representational systems, and the *emergent systems* approach, embracing connectionist systems, dynamical systems, and enactive systems, all based to a lesser or greater extent on principles of self-organization [8], [9].

Cognitivist approaches correspond to the classical and still common view that cognition is a type of computation [10], a process that is symbolic, rational, encapsulated, structured, and algorithmic [11]. In contrast, advocates of connectionist, dynamical, and enactive systems approaches argue in favour of a position that treats cognition as emergent, self-organizing, and dynamical [12].

Although the use of symbols is often presented as definitive difference between the cognitivist and emergent positions, they differ more deeply and more fundamentally, well beyond a simple distinction based on symbol manipulation. For example, each adopts a different stance on computational operation, representational framework, semantic grounding, temporal constraints, inter-agent epistemology, embodiment, perception, action, anticipation, adaptation, motivation, and autonomy [3].

Cognitivism asserts that cognition involves computations defined over internal representations of knowledge, in a process whereby information about the world is abstracted by

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perception, and represented using some appropriate symbolic data-structure, reasoned about, and then used to plan and act in the world. The approach has also been labelled by many as the *information processing* (or symbol manipulation) approach to cognition [8], [11]–[17]

For cognitivists, cognition is representational in a strong and particular sense: it entails the manipulation of explicit symbolic representations of the state and behaviour of the external world and the storage of the knowledge gained from experience to reason even more effectively in the future [18]. Perception is concerned with the abstraction of faithful spatio-temporal representations of the external world from sensory data.

In most cognitivist approaches concerned with the building artificial cognitive systems, the symbolic representations are initially at least the product of a human designer: the designer's description of his view of the world. This is significant because it means that these representations can be directly accessed and interpreted by others. It has been argued that this is also the key limiting factor of cognitivist systems as these programmer-dependent representations effectively blind the system [19], constraining it to an idealized description that is a consequence of the cognitive requirements of human activity. This approach works well as long as the assumptions that are implicit in the designer model are valid. As soon as they are not, the system fails. Sometimes, cognitivist systems deploy machine learning and probabilistic modelling in an attempt to deal with the inherently uncertain and incomplete nature of the sensory data that is being used to drive this representational framework. However, this doesn't alter the fact that the representational structure is still predicated on the descriptions of the designers.

Emergent approaches take a very different view of cognition. They view cognition as the process whereby an autonomous system becomes viable and effective in its environment. It does so through a process of self-organization through which the system is continually re-constituting itself in real-time to maintain its operational identity. For emergent approaches, perception is concerned with the acquisition of sensory data in order to enable effective action [20] and is dependent on the richness of the action interface [21]. It is not a process whereby the structure of an absolute external environment is abstracted and represented in a more or less isomorphic manner.

In contrast to the cognitivist approach, many emergent approaches assert that the primary model for cognitive learning is anticipative skill construction rather than knowledge acquisition, and that processes which both guide action and improve the capacity to guide action while doing so are taken to be the root capacity for all intelligent systems [22]. Cognitivism entails a self-contained abstract model that is disembodied in principle and the physical instantiation of the systems plays no part in the model of cognition [4], [23]. In contrast, emergent approaches are intrinsically embodied and the physical instantiation plays a pivotal role in cognition.

III. EMBODIMENT

What exactly it is to be embodied? One form of embodiment, and clearly the type envisaged by proponents of the emergent systems approach to cognition, is a physically-active body capable of moving in space, manipulating its environment, altering the state of the environment, and experiencing the physical forces associated with that manipulation [24]. But there are other forms of embodiment. Ziemke introduced a framework to characterize five different types of embodiment [25], [26]:

1) *Structural coupling* between agent and environment in the sense a system can be perturbed by its environment and can in turn perturb its environment.
2) *Historical embodiment* as a result of a history of structural coupling;
3) *Physical embodiment* in a structure that is capable of forcible action (this excludes software agents);
4) *Organismoid embodiment, i.e.* organism-like bodily form (*e.g.* humanoid or rat-like robots); and
5) *Organismic embodiment* of autopoietic living systems.

This list is ordered by increasing specificity and physicality. Structural coupling entails only that the system can influence and be influenced by the physical world. A computer controlling a power-plant or a computerized cruise control in a passenger car would satisfy this level of embodiment. A computer game would not necessarily do so. Historical embodiment adds the incorporation of a history of structural coupling to this level of physical interaction so that past interactions shape the embodiment. Physical embodiment is most closely allied to conventional robot systems, with organismoid embodiment adding the constraint that the robot morphology is modelled on specific natural species or some feature of natural species. Organismic embodiment corresponds to living beings.

Despite the current emphasis on embodiment in cognitive system research, Ziemke argues that many current approaches in cognitive robotics and epigenetic robotics still adhere to the functionalist hardware/software distinction in the sense that the computational model does not in principle involve a physical instantiation and, furthermore, that all physical instantiations are equivalent as long as they support the required computations. Ziemke notes that this is a significant problem because the fundamental idea underpinning embodiment is that the morphology of the system is actually a key component of the systems dynamics. The morphology of the cognitive system not only matters, it is a constitutive part of the cognitive process.

IV. THE ROLE OF ROBOTICS IN COGNITION

Cognitivist systems do not need to be embodied. They are functionalist in principle [5]: cognition comprises computational operations defined over symbolic representations and these computational operations are not tied to any given instantiation. Although any computational system requires some physical realization to effect its computations, the underlying computational model is independent of the physical platform on which it is implemented. For this reason, it has also been noted that cognitivism exhibits a form of mind-body dualism [11], [24].

Cognitivism is also positivist in outlook: all cognitive systems — designer and designed — share a common universallyaccessible and universally-representable world that is apprehended by perception. Consequently, symbolic knowledge about this world, framed in the concepts of the designer, can be programmed in directly and doesn't necessarily have to be developed by the system itself through exploration of the environment. Some cognitivist systems exploit learning to augment or even supplant the *a priori* designed-in knowledge and thereby achieve a greater degree of adaptiveness and robustness. Embodiment at any of the five levels identified in the previous section may offer an additional degree of freedom to facilitate this learning, but it is by no means necessary.

The perspective from emergent systems is diametrically opposed to the cognitivist position. Emergent systems, by definition, must be embodied and embedded in their environment in a situated historical developmental context [11]. Furthermore, the physical instantiation plays a direct constitutive role in the cognitive process [4], [27], [28].

To see why embodiment is a necessary condition of emergent cognition, consider again what cognition means in the emergent paradigm. It is the process whereby an autonomous system becomes viable and effective in its environment. In this, there are two complementary things going on: one is the self-organization of the system as a distinct entity, and the second is the coupling of that entity with its environment. "Perception, action, and cognition form a single process" [24] of *self-organization in the specific context of environmental perturbations of the system*. This gives rise to the ontogenic development of the system over its lifetime. This development is identically the cognitive process of establishing the space of mutually-consistent couplings. These environmental perturbations don't control the system since they are not components of the system (and, by definition, don't play a part in the self-organization) but they do play a part in the ontogenic development of the system. Through this ontogenic development, the cognitive system develops its own epistemology, *i.e.* its own system-specific knowledge of its world, knowledge that has meaning exactly because it captures the consistency and invariance that emerges from the dynamic self-organization in the face of environmental coupling. Thus, we can see that, from this perspective, cognition is inseparable from 'bodily action' [24]: *without physical embodied exploration, a cognitive system has no basis for development.*

V. ENACTION

Enactive systems [8], [19], [20], [29]–[32] take the emergent paradigm one step further. The five central concepts of enactive cognitive science are embodiment, experience, emergence, autonomy and sense-making [2], [33]. In contradistinction to cognitivism, which involves a view of cognition that requires the representation of a given objective pre-determined world [8], [34], enaction asserts that cognition is a process whereby the issues that are important for the continued existence of a cognitive entity are brought out or enacted: co-determined by the entity as it interacts with the environment in which it is embedded. The term co-determination [20] is laden with meaning. It implies that the cognitive agent is deeply embedded in the environment and specified by it. At the same time, it implies that the process of cognition determines what is real or meaningful for the agent. In other words, the system's actions define the space of perception. This space of perceptual possibilities is predicated not on an objective environment, but on the space of possible actions that the system can engage in whilst still maintaining the consistency of the coupling with the environment. Co-determination means that the agent constructs its reality (its world) as a result of its operation in that world. In this context, *cognitive behaviour is inherently specific to the embodiment of the system and dependent on the system's history of interactions,* i.e., *its experiences.* Thus, nothing is 'pre-given'. Instead there is an enactive interpretation: a real-time context-based choosing of relevance (*i.e.* sense-making).

For cognitivism, the role of cognition is to abstract objective structure and meaning through perception and reasoning. For enactive systems, the purpose of cognition is to uncover unspecified regularity and order that can then be construed as meaningful because they facilitate the continuing operation and development of the cognitive system. In adopting this stance, the enactive position challenges the conventional assumption that the world *as the system experiences it* is independent of the cognitive system ('the knower'). Instead, knower and known 'stand in relation to each other as mutual specification: they arise together' [8].

For an enactive system, knowledge is the effective use of sensorimotor contingencies grounded in the structural coupling in which the nervous system exists. Knowledge is particular to the system's history of interaction. If that knowledge is shared among a society of cognitive agents, it is not because of any intrinsic abstract universality, but because of the consensual history of experiences shared between cognitive agents with similar phylogeny and compatible ontogeny.

The knowledge possessed by an enactive system is built on sensorimotor associations, achieved initially by exploration, and affordances.[1] However, this is only the beginning. The enactive system uses the knowledge gained to form new knowledge which is then subjected to empirical validation to see whether or not it is warranted (we, as enactive beings, imagine many things but not everything we imagine is plausible or corresponds well with reality, *i.e.* our phenomenological experience of our environment).

One of the key issues in cognition, in general, and enaction, in particular, is the importance of internal simulation in accelerating the scaffolding of this early developmentally-acquired sensorimotor knowledge to provide a means to:

1) predict future events;
2) explain observed events (constructing a causal chain leading to that event);
3) imagine new events.

Crucially, there is a need to focus on (re-)grounding predicted, explained, or imagined events in experience so that the system — the robot — can *do* something new and interact with the environment in a new way.

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[1] For true enaction, everything is affordance since everything that is experienced is contingent upon the systems own spatiotemporal experience and embodiment.

The dependence of a cognitive system's perceptions and knowledge on its history of coupling (or interaction) with the environment and on the very form or morphology of the system itself has an important consequence: there is no guarantee that the resultant cognition will be consistent with human cognition. This may not be a problem, as long as the systems behaves as we would wish it to. On the other hand, if we want to ensure compatibility with human cognition, then we have to admit a stronger humanoid form of embodiment and adopt a domain of discourse that is the same as the one in which we live: one that involves physical movement, forcible manipulation, and exploration [35].

VI. CHALLENGES

The adoption of an embodied approach to the development of cognitive systems poses many challenges. We highlight just a few in the following.

The first challenge is the identification of the phylogenetic configuration and ontogenetic processes. Phylogeny — the evolution of the system configuration from generation to generation — determines the sensory-motor capabilities that a system is configured with at the outset and that facilitate the system's innate behaviours. Ontogenetic development — the adaptation and learning of the system during its lifetime — gives rise to the cognitive capabilities that we seek. To enable development, we must somehow identify a minimal phylogenic state of the system. In practice, this means that we must identify and effect perceptuo-motor capabilities for the minimal behaviours that ontogenetic development will subsequently build on to achieve cognitive behaviour.

The requirements of real-time synchronous system-environment coupling and historical, situated, and embodied development pose another challenge. Specifically, the maximum rate of ontogenic development is constrained by the speed of coupling (*i.e.* the interaction) and not by the speed at which internal processing can occur [19]. Natural cognitive systems have a learning cycle measured in weeks, months, and years and, while it might be possible to condense these into minutes and hours for an artificial system because of increases in the rate of internal adaptation and change, it cannot be reduced below the time-scale of the interaction. You cannot short-circuit ontogenetic development because it is the agent's own experience that defines its cognitive understanding of the world in which it is embedded. This has serious implications for the degree of cognitive development we can practically expect of these systems.

Development implies the progressive acquisition of predictive anticipatory capabilities by a system over its lifetime through experiential learning. Development depends crucially on motivations which underpin the goals of actions. The two most important motives that drive actions and development are social and explorative. There are at least two exploratory motives, one focussing on the discovery of novelty and regularities in the world, and one focussing on the potential of one's own actions. A challenge that faces all developmental embodied robotic cognitive systems is that of modeling these motivations and their interplay, and identifying how they influence action.

Enactive systems are founded on the principle that the system discovers or constructs for itself a world model that supports its continued autonomy and makes sense of that world in the context of the system's own morphology-dependent coupling or interaction with that world. The identification of such generative self-organizing processes is pivotal to the future progress of the field. While much current research concentrates on generative processes that focus on sensorimotor perception-action invariances, such as learning affordances, it is not clear at present how to extend this work to generate the more abstract knowledge that will facilitate the prediction, explanation, and imagination that is so characteristic of a true cognitive system.

Finally, development in it fullest sense represents a great challenge for robotics. It is not just the state of the system that is subject to development but also the very morphology, physical properties, and structure of the system — the kinematics and dynamics — that develop and contribute to the emergence of embodied cognitive capabilities. To realize this form of development, we will need new adaptive materials and a new way of thinking to integrate them into our models of cognition.

VII. CONCLUSIONS

Cognitivist systems are dualist, functionalist, and positivist. They are dualist in the sense that there is a fundamental distinction between the mind (the computational processes) and the body (the computational infrastructure and, where required, the devices that effect any physical interaction). They are functionalist in the sense that the actual instantiation and computational infrastructure is inconsequential: any instantiation that supports the symbolic processing is sufficient. They are positivist in the sense that they assert a unique and absolute empirically-accessible external reality that can be modelled and embedded in the system by a human designer. Consequently, embodiment of any type plays no necessary role.

In the enactive paradigm, the situation is the reverse. The perceptual capacities are a consequence of an historic embodied development and, consequently, are dependent on the richness of the motoric interface of the cognitive agent with its world. That is, the action space defines the perceptual space and thus is fundamentally based in the frame-of-reference of the agent. Consequently, the enactive position is that cognition can only be created in a developmental agent-centred manner, through interaction, learning, and co-development with the environment. It follows that, through this ontogenic development, the cognitive system develops its own epistemology, *i.e.* its own system-specific knowledge of its world, knowledge that has meaning exactly because it captures the consistency and invariance that emerges from the dynamic self-organization in the face of environmental coupling.

Despite the current emphasis on embodiment in cognitive systems research, many current approaches in cognitive & epigenetic robotics still adhere to the functionalist dualist hardware/software distinction. It is not yet clear that researchers have embraced the deep philosophical and scientific commitments of adopting an enactive approach to embodied robotic cognitive systems: the non-functionalist, non-dualist, and non-positivist stance of enaction. It is non-functionalist since the robot body plays a constitutive part in the cognitive process and is not just a physical input-output device. It is non-dualist since there is no distinction between body and mind in the dynamical system that constitutes a cognitive system. It is non-positivist since knowledge in an enactive system is phenomenological and not directly accessible; the best we can hope for is a common epistomology deriving from a shared history of experiences.

There are many challenges to be overcome in pushing back the boundaries of cognitive systems research, particularly in the area of enaction. Foremost among these is the difficult task of identifying the necessary phylogeny and ontogeny of an artificial cognitive system: the requisite cognitive architecture that facilitates both the system's autonomy (*i.e.* its self-organization and structural coupling with the environment) and its capacity for development and self-modification. To allow true ontogenetic development, this cognitive architecture must be embodied in a way that allows the system the freedom to explore and interact and to do so in an adaptive physical form that enables the system to expand its space of possible autonomy-preserving interactions. This in turn creates a need for new physical platforms that offer a rich repertoire of perception-action couplings and a morphology that can be altered as a consequence of the system's own dynamics. In meeting these challenges, we move well beyond attempts to build cognitivist systems that exploit embedded knowledge and which try to see the world the way we designers see it. We even move beyond learning and self-organizing systems that uncover for themselves statistical regularity in their perceptions. Instead, we set our sights on building enactive phenomenologically-grounded systems that construct their own understanding of their world through adaptive embodied exploration and social interaction.

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