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ROBOT SPATIAL LEARNING: INSIGHTS FROM ANIMAL AND HUMAN BEHAVIOUR

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Natural systems embody robust solutions to difficult problems, hence research in robotics should benefit by looking for clues in the understanding of natural systems for the design of the artificial. The literature on spatial learning in natural systems, suggests that there is a great diversity of solutions to the problem of learning and navigating a large-scale environment. Although on a species level the solutions employed are specialised, it is argued here that there are characteristic properties that extend across species and suggest principles of general importance for the design of autonomous mobile robots. In particular, it is proposed that that there is a commonality in many natural navigation systems relating to the use of multiple sub-systems for the control of behaviour, and the exploitation of dynamic, quantitative representations of space. In the following, evidence from studies of animal and human navigation is briefly reviewed followed by a summary of a number of key themes of relevance to the design of systems for spatial learning and navigation in mobile robots.

Animal navigation

The literature on animal spatial learning differentiates the navigation skills of most invertebrates and lower vertebrates, from those of higher vertebrates (birds and mammals). In particular, it suggests that many invertebrates rely on path integration mechanisms, compass senses, and piloting [15], to negotiate large-scale space. Importantly, invertebrates do not appear to memorise the spatial layout of their environment, and as a consequence, their navigation behaviour may be restricted to homing and retracing familiar routes [16]. In contrast, there is evidence that higher vertebrates do learn the spatial layout of their environments (see, for example, [5, 9]) enabling them to generate and follow more efficient paths to distant targets. The literature on vertebrate navigation further suggests a discontinuity between route knowledge and the use of quantitative (metric) representations of space. For instance, O'Keefe [9] has argued that there are two largely separate navigation systems used by mammals including man. The first of these, which he calls the *taxon* system, is supported by chains of associations and underlies some of the route-following abilities seen in animals. O'Keefe's second system, called the *locale* system, constructs a layout model describing the metric spatial relations between locations in the environment. Evidence for the existence of this system and its independence from taxon strategies consists of both observational and laboratory studies of animal behaviour, and neurophysiological studies suggesting that different brain structures underlie the two systems.

O'Keefe's [9] distinction between taxon and locale systems follows a long line of research into 'response' versus 'place' knowledge in animal navigation that shows the existence of complimentary navigation systems in animals. This literature also demonstrates, that there may be no simple hierarchical arrangement of control for arbitrating between these systems. For instance, in experiments on the maze learning behaviour of rats, response knowledge (chained motor responses) appeared to predominate in some experimental situations and place knowledge (encoded spatial relations) in others. Behavioural studies with many different animal species (e.g. [1, 2, 4]) and with humans (see [13]), have now demonstrated the importance of multiple systems for

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achieving navigational goals, and the existence of mechanisms for arbitrating between the alternative solutions these systems generate.

Human navigation

The literature on human navigation has sometimes been regarded as a source of inspiration for qualitative (rather than quantitative) navigation methods for autonomous agents. Such a view arises naturally from the theory pioneered by Piaget [10], and later supported by both experimental and observational research (e.g. [14]), that human spatial knowledge has a hierarchical structure and is acquired through a stage-like process. For Piaget a fundamental stage in the acquisition of spatial knowledge is the construction of qualitative models of the environment from more elementary sensorimotor associations (this representation may be supplemented later by distance and direction information to form a more detailed quantitative map). A number of computational models, must notably those of Kuipers (e.g. [7]), have been inspired by these proposals and stress the importance of building topological models of space.

One of the difficulties, however, with some early studies on human navigation was the assumption that a quantitative 'cognitive map' would be something like an image of a cartographic map. Experiments that found errors in spatial knowledge—distortion, gaps, holes, fault-lines, and asymmetries—were therefore taken as evidence against the use metric representations and in favour of more qualitative systems. However, although there is little support for this notion of a metric "picture in the head" (see, for instance, [6]), there is good evidence that metric spatial representations, of a quite different kind, form an important element of human navigation competence (see [8, 13] for reviews). Some of the distinctive properties of these representations are demonstrated in an experiment by Scholl [12], which contrasted the spatial knowledge acquired through direct experience of the environment with that acquired indirectly by memorising a cartographic map. In the case of knowledge acquired from a map, a task of 'pointing to unseen targets' showed that the stored representation had a preferred orientation—pointing was easier when the subject was aligned with the North-South axis of the map. Further, with this type of knowledge all coded locations could be accessed with equal ease (as though one was 'looking down' on an aerial map of the environment). In contrast knowledge acquired from direct experience showed no preferred (absolute) orientation although, importantly, targets in front of the body were located more easily than ones behind. In [13] Scholl argues, on the basis of a number of studies of this nature, that human cognitive spatial representations encode environment-centred representations of spatial relations abstracted from the stream of local egocentric views experienced during movement. Furthermore, this store of knowledge has no inherent orientation—whenever the representation of the world is accessed it is automatically aligned with the body, anticipating objects that are about to become visible. From this view, the internal representation is not a static model within which the navigator tracks his or her own position and orientation. Instead, the human 'cognitive map' appears to be an active representational system in which perceptual experience evokes a set of expectations that are always centred and oriented to the navigator's current perspective.

Implications for robotics

The above observations lend support to the essentially pragmatic approach of recent research in situated robotics to navigation tasks (e.g. Connell [3]) which has begun by developing competences similar to O'Keefe's taxon systems that exploit the good odometry information available to robots and use chains of acquired associations to implement route following strategies. However, to achieve navigation skills of the more powerful and flexible variety seen in vertebrates, taxon strategies must be complimented by mechanisms that encode the spatial layout of the environment. The evidence from natural systems cited here supports the construction of representations of space that encode metric spatial relations. However, as in natural systems, the navigation task may be shared between multiple interacting sub-systems, where each subsystem builds its own partial representation of the world. In [11] I have argued that much of the above evidence supports the construction of relational models of space in which locations are redundantly encoded with respect to multiple local coordinate frameworks. By constructing a network in which neighbouring frameworks are linked, large-scale spatial relations can be accessed by propagating local view information. Such a structure forms a representation of the environment that has has no inherent orientation, yet, as with the human cognitive map, can generate a dynamic description of the environment that is automatically oriented to the agent's current perspective and position.

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