Robot See, Robot Do : An Overview of Robot Imitation

Paul Bakker and **Yasuo Kuniyoshi**
Autonomous Systems Section
Intelligent Systems Division
Electrotechnical Laboratory
Tsukuba Science City
Japan

bakker,kuniyosh@etl.go.jp

Abstract

There are currently two major approaches to robot teaching: explicitly tell the robot what to do (programming) or let the robot figure it out for itself (reinforcement learning/genetic algorithms). In this paper we give an overview of a new approach, in which the robot instead learns novel behaviours by observing *the behaviour of others:* imitation learning. *We summarize the psychological background of this approach, propose a definition of imitation, and identify the important issues involved in implementing imitation in robotic systems. Based on this framework, we review recent published work in this area, and describe an imitation project currently underway at the Electrotechnical Laboratory in Japan.*

Introduction

Ever since the conception of robots, researchers have been faced with the problem of how to make them *behave*. That is, how to endow robots with the ability to perform complex behaviours and interact intelligently with the environment.

The two most widely-used solutions to this problem have taken diametrically opposed approaches: either *tell* the robot in detail what it has to do (e.g., robot programming), or, at the other extreme, provide the robot with a simple *learning* strategy and let it figure out, through interaction with the environment, appropriate behaviours for itself (e.g., Drescher, 1991).

Both approaches have proven to be insufficient to control robot behaviour in practice. Robot programming is simply too hard; it is difficult and tedious to describe complex behaviours to robots in sufficient detail, and to specify exhaustively how they should adapt to novel situations.

Robot learning, on the other hand, presently lacks power. Robots are expected to learn too much with too little information. The learning paradigms that have so far been employed (such as reinforcement learning and genetic algorithms) have proven too weak to learn any behaviours of interest. While they have the theoretical potential to learn everything, in practice they are apparently unable to learn *anything* (Brooks & Mataric, 1993).

The recent work in so-called behaviour-based robotics, and the related animat approach (Maes, 1993) is an attempt to scale back the learning task confronting the robot. It does this by using a combination of the programming and learning approaches: a robot is *programmed* with a set of basic behaviours, and is expected to *learn* how to coordinate these behaviours so as to maximize performance (Brooks & Mataric, 1993). While this approach has had some good results in learning low-level reactive behaviours, serious questions have been raised about its capacity to scale to higher-level intelligent behaviour (Tsotsos, 1995).

In this paper, we examine a new approach to robot learning that similarly takes an intermediate stance between learning and programming. This approach is *learning by imitation.* Put simply, it enables the robot to learn new behaviours by observing other agents – be they human or robot – operating in its environment. Instead of learning in solitude, agents are now able to benefit from the experience of others. One could either view imitation as an improved *learning* paradigm, that provides the learning robot with richer information about its environment, or alternatively as a simpler approach to *programming* that allows one to communicate new behaviours to the robot by 'showing' instead of 'telling'.

A spate of recent papers on robot imitation by researchers in Japan, Europe and Australia (Hayes & Demiris, 1994; Kuniyoshi, Inaba, & Inoue, 1994; Kuniyoshi, 1994; Dautenhahn, 1995) reflects the current interest in the robot community in the potential of this new approach.

As the first steps are now being taken towards implementing imitation in autonomous robots, we considered it timely to prepare an introductory overview of the concept of imitation. Imitation is an established – and controversial – topic in psychology. The issues highlighted in the psychological literature are discussed in the next section, where we also propose a mechanistic definition of imitation. Subsequent sections of this paper review the potential benefits of imitation learning for robots, and outline the major issues involved in the implementation of imitation learning. A suggested framework for mapping progress in robot imitation is then introduced, and is used to briefly review the published work on robot imitation to date.

Finally, we describe an ongoing project at the Electrotechnical Laboratory in Japan, that aims to have a robot *develop* the ability to imitate.

What Exactly is Imitation?

While imitation can be considered a new topic in robotics, it has a long history of study and controversy in the fields of ethology and experimental psychology. The controversy has mainly centred on a question that may prove to be of prime importance in robot work as well: what does 'imitation' really mean?

By resolving this contentious issue at an early stage, we can hopefully avoid the terminological problems that have plagued the study of imitation in psychology (Galef, 1988). It will also give us a clear foundation from which to discuss the promise of imitation in robotics and to evaluate the contributions of recent work.

At the turn of the century, great interest was generated by the question of whether animals shared any of man's advanced cognitive abilities[1]. One of the cognitive abilities in question was learning by imitation.

Imitation was succinctly defined at the time to be:

> *From an act witnessed learn to do an act* (Thorndike, 1911, p. 79).

Observation of animal behaviour *seemed* to confirm many clear cases of imitation. For example, chicks following their mother's example in avoiding roads, feeding only in certain areas, and eating certain species of plants; birds learning to puncture and feed from milk bottles; and kittens, exposed to adult cats that attained food by manipulating levers, learning to perform the same manipulations much faster than a control group (Galef, 1988).

The evidence seemed compelling, but it was eventually realized that the behaviours described above were not necessarily the result of 'witnessing' an act and learning it: they could be more parsimoniously explained by an interplay of simpler mechanisms such as *reinforcement learning*, *following behaviour*, *social facilitation*, *matched dependent behaviour* and *stimulus enhancement*.

[1] The answer to this question was considered at the time to be an important test of evolution theory – see Galef (1988).

In the cat experiment cited above, for example (Chesler, 1969), the kittens may have been more likely to manipulate the lever simply because the adult cat had left a scent on it. A chance pawing of the lever then led to reinforcement and subsequent repetition of the behaviour. Similarly, many of the apparent imitatory behaviours of birds can be explained by the innate following behaviour of chicks.

Such alternative learning mechanisms, which together have the same *behavioural result* as imitation (i.e., the spread of similar behaviours amongst animals) were unfortunately (and confusingly) labelled as special cases of imitation in the literature: instinctive imitation, pseudo-imitation, reflective imitation and so on (Galef, 1988). Imitation, as defined above, was relabelled 'true imitation'!

It is our submission that in robot imitation we are chiefly interested in 'true imitation', as described by Thorndike: a behaviour is observed, understood, and reproduced. Our goal is to investigate how robots can be endowed with this powerful learning mechanism. Any other form of 'imitation' that does not involve the adoption of a behaviour from the *observation* of that behaviour will be precluded from our discussion.[2]

This is not to say that the simple mechanisms noted above, which may be used to control the contagion of behaviours in societies of robots, are not worthy of study in their own right. Indeed, we are pursuing this direction in more detail elsewhere (Bakker, 1996b). It is simply proposed that they not be included under the banner of 'robot imitation', to avoid a terminological confusion.

Our definition of imitation is therefore stated in terms of the *mechanism* involved:[3]

> **Imitation takes place when an *agent* learns a *behaviour* from observing the execution of that behaviour by a *teacher*.**

Note that the roles of 'teacher' and 'agent' are not fixed; they can be reversed from one encounter to the next, for example during bouts of mutual imitation (Piaget, 1962).

The Promise of Imitation

In this section we discuss the reasons why we should be interested in endowing robots with the ability to imitate. What specific advantages would such a learning mechanism give? As will become clear below, the advantages are varied and quite substantial, both for individual agents and for societies of interacting agents.

Adaptation

An agent with the ability to imitate has an excellent mechanism for adapting to its environment. By observing other agent's actions, the agent can quickly learn new behaviours that are *likely* to be useful; likely, because they are already being used by agents successfully operating in the *same* environment.

Imitation also acts as an *ongoing* means of adaptation, allowing the agent to induct new behaviours from fellow agents as the environment changes, new skills are discovered by other agents, or as the agent moves to a new setting.

Efficient Communication

Imitation provides agents with an efficient non-verbal means of communication. Because it is non-verbal, it does not require the teacher and the agent to 'speak the same language'. This is also true at the somatic level: agents can learn from other agents that are of a different species or are built from different hardware.

[2] The term 'observation' here includes perception through *any* of the robot's available faculties: "To see *or sense*, esp. through directed careful analytic attention" (Webster Online Dictionary).

[3] Compare this to the more 'behaviouristic' definition offered in a psychological text: *Imitation is the motoric or verbal performance of specific acts or sounds that are like those previously performed by a model* (Yando, Seitz, & Zigler, 1978). Such a definition does not preclude the various types of pseudo-imitation outlined above.

The basic reason for this advantage is that communication via imitation takes place at a high level (i.e., in terms of actions) rather than at a lower level (such as motor commands).

Communication via imitation is also efficient because a large amount of important information can be transmitted *simultaneously* with each act – the context in which it occurs, the objects that are manipulated, the outcomes, and the tools involved.

Finally, imitation has the advantage of being an undemanding and unobtrusive communication method because a teacher does not have to go 'off-line' to transfer a behaviour to an agent: the agent (or multiple agents simultaneously) can learn by observing the teacher without interfering in the teacher's performance.

Compatibility with other Learning Mechanisms

Imitation can be used as a learning mechanism in conjunction with existing learning schemes for agents (such as reinforcement learning, trial-and-error learning, or symbolic induction schemes). While the current work examines imitation learning in isolation, it can naturally be used as a supplemental learning strategy, increasing the agents' learning capabilities overall.

Efficient Learning

The most significant advantage of robot learning by imitation promises to be the *efficiency* of the learning process, particularly in a *society* of agents. This follows from the communication and compatibility facets discussed above.

In the traditional learning paradigm for robots, each agent is 'alone' in the environment. All new behaviours must be discovered through personal learning experience. Imitation opens a rich new vein of information to the learning robot: the behaviours of other agents operating in the same environment.

When one agent gains a useful new behaviour – be it by trial and error, observing a human, or simply from being reprogrammed – imitation provides a mechanism for rapidly communicating the discovery of this behaviour through the whole society of agents. It provides a means of *combining* the power of all the agents' diverse learning schemes, to benefit the whole society.

Imitation thereby increases the adaptation and survivability of a society as a whole. It also ensures the survival of useful *behaviours* – such behaviours will rapidly spread, and may even be passed on to following generations.

'Good Company'

A final point is that providing robots with imitation ability gives them a skill that has thus far only been demonstrated in higher animals – primates, cetaceans and humans. These are also the only animals that we consider to exhibit advanced intelligence. Based on the advantages outlined above, learning by imitation would seem to be one of the major components of general intelligent behaviour. Robots with imitatory ability may hence find themselves in ethologically 'good company' for displaying truly intelligent behaviour.

Implementation Issues in Robot Imitation

After the discussion of the prospective benefits of imitation given above, one might well wonder what kind of oversight has led to its exclusion from robot learning thus far! The answer is, of course, that there is a good reason why imitation in nature is restricted to higher animals – imitation itself requires significant perceptual and cognitive abilities. Understanding (much less implementing) many of these abilities is still an open problem in psychology, artificial intelligence, and robotics.

Nevertheless, the first few tentative steps towards robot imitation have already been taken. Some of the recent work will be reviewed in the next section; the purpose of this section is to identify the substantive issues that must be addressed before robots can be considered able to imitate.

The following list is based on our own research, and from analyzing the problems addressed (and purposefully avoided) in recent work in robotics. While probably not an exhaustive list, it does outline what is *at least* required to implement imitation in an autonomous agent. The list also suggests a framework for reviewing future contributions to this area.

A Conceptual Framework for Robot Imitation

Imitation in robots (or in animals, or humans) would appear to be composed of three fundamental processes, described by Kuniyoshi et al. (1994) as "seeing, understanding and doing" (p. 800). In a reformulation of this statement, we will propose that for an *agent* to imitate an action by a *teacher*, it must at least:

1. *observe* the action,
2. *represent* the action,
3. and *reproduce* the action

Each of these fundamental processes in turn involve some important problems:

Observation

- Motivate the agent to observe a teacher;
- Identify an appropriate teacher to observe;
- Identify when the teacher is performing an action that should be learned;
- Accurately observe the teacher's action (via vision or some other sense – includes tracking, attention and segmentation issues);
- Process the relevant environmental information accompanying the action – the context in which the action occurred, the participants, the tools or objects manipulated.

Representation

- Choose an appropriate representation for actions;
- Convert an observed action to the agent's internal representation (this subsumes an *analogy* mapping problem – mapping the teacher's actuators to the agent's actuators).

Reproduction

- Motivate the agent to consider executing an observed action;
- Choose the appropriate context in which to reproduce the action;
- Adapt the action to the current environment.

A Review of Recent Work in Robot Imitation

Here follows a brief review of recent work in robot imitation. We will discuss these papers in the context of the framework described above, highlighting for each paper the issues that were addressed, and those which were (purposefully) avoided.

Kuniyoshi et al. (1994)

In Kuniyoshi et al. (1994), a robot agent watches a human teacher performing a simple assembly task in a tabletop environment. The motor movements of the human are classified as actions known to the robot (*pick*, *move*, *place* etc.). When the assembly task is completed, the robot is commanded to reproduce the sequence of actions. It can successfully do this even if the initial position of the items to be manipulated has changed.

Observation. The authors chose to focus on the problem of *perceiving* the teacher's actions: determining the start and finish points of actions, and tracking the human hand. This problem is simplified by the fact that the robot is only required to *recognize* actions that it already knows.

The robot was not required to choose which teacher or which actions to observe: *all* actions had to be observed in 'seeing' mode, and then reproduced in 'doing' mode.

Representation. The problem of mapping action sequences to the robot's actuators was solved by using symbolic labels. Once the robot correctly interpreted a human action, the label could be mapped to a pre-programmed robot action sequence.

Reproduction. The robot was explicitly told when to reproduce the observed actions, by being switched to 'doing' mode. Kuniyoshi et al. (1994) focused on the problem of how to *adapt* the imitated action to the current environment. The initial state of the table was analyzed, and the parameters of the action sequence were changed to conform to this state (e.g., if the position of objects on the table has changed between the seeing and doing modes).

To sum up, Kuniyoshi et al. (1994) addressed two fundamental problems: how to accurately perceive teacher's actions, and how to adapt an imitated action to the environment in which it is reproduced.

Hayes and Demiris (1994)

In Hayes and Demiris (1994), a robot agent is taught the skill of maze traversal by imitation. The agent follows a teacher robot through a maze, detecting significant teacher actions (such as turning), and physically copying those actions. The agent also learns to associate the environment – the position in the maze (in terms of local wall positions) – with the teacher's actions.

Observation. There is only one teacher to attend to, and it must be watched (and followed) at all times in training mode. The identification of teacher actions is simplified by restricting the teacher to two essential acts: turning by 90 degrees and moving straight ahead.

Representation. The problem of mapping actions from the teacher to the agent is elegantly solved by commanding the agent to always follow the teacher. Through the act of following, it must *immediately* imitate the teacher's locomotive action. This agent action (turning or moving straight ahead) is then stored with the environmental information.

Actions are represented as symbolic rules. The antecedent of such a rule is a description of the environment in which an action occurred, and the RHS is the action to be executed in that environment. For example, right-hand turns become associated with an environment in which there is one wall to the left and one straight ahead.

Reproduction. When the agent attempts to navigate the maze by itself, it constantly tries to match the perceived environment to the antecedents of stored production rules. The issue of motivation is thus avoided: in this mode, the agent is *always* and *only* looking to reproduce observed actions.

In summary, Hayes and Demiris (1994) addressed two major issues: how to *map* a teacher action to an agent action, and how to learn *when* to reproduce an observed action. The solutions implemented by Hayes and Demiris (1994) are simple and elegant, but only work because of the simplicity of the maze environment and the restricted set of locomotive actions available.

Dautenhahn (1995)

In Dautenhahn (1995), agents traverse a 'hilly landscape', attaching themselves to teacher robots and imitating their trajectories. As in Hayes and Demiris (1994), imitation is so far limited to the act of following of other agents.

Observation. Agents are explicitly programmed to seek out other agents and attach themselves. Eventually agents learn to recognize suitable teachers from positive (or negative) learning experiences in the past.

Representation. The problem of interpreting teacher actions is implicitly solved by the fact that the set of possible actions is very simple – movement in a given direction – and the agent robot can map these actions to its own body by following the teacher.

Reproduction. Learned movements are associated with the local gradient in the hilly landscape. This would allow the agent to generalize behaviours to other, similar areas in the hilly landscape.

In summary, Dautenhahn (1995) proposes an environment for robots to learn social behaviours in which imitation plays a small role. The implementation of the imitation behaviour is similar to Hayes and Demiris (1994) in that imitation is limited to copying the directional movements of the teacher, and associating these movements with the characteristics of the environment.

Graphical Summary

Figure 1 reviews the list of identified issues in robot imitation given above, and shows which of these issues have been (partially) addressed in the papers reviewed here. Many more of the fundamental problems identified need to be tackled before a general-purpose imitating robot can be realized. Hopefully, the framework can be used to make explicit the particular problem areas that future works address in robot imitation, and to measure overall progress towards that goal.

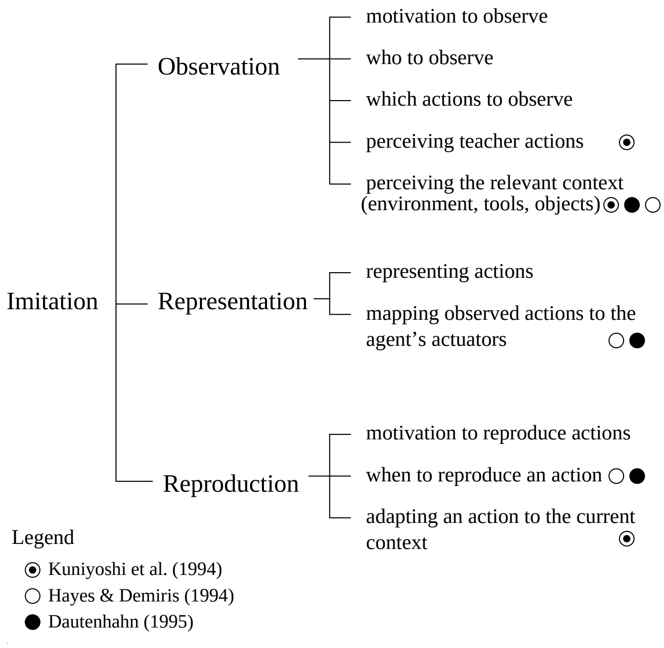

Figure 1: A graphical overview of the issues involved in implementing imitation, and the work carried out in the papers reviewed here.

An Overview of an Imitation Project at ETL

In this section, we describe an ongoing project at the Electrotechnical Laboratory (ETL) that addresses one of the critical issues in robot imitation identified in the framework above. The project aims to produce a control architecture for robots that allows them to *develop* the ability to imitate, by approximately recapitulating the developmental acquisition of the imitation skill by human infants.

This is one of several projects involving imitation that are being pursued by members of the Cognitive Robotics Research Group at ETL. One of the long-term goals of this group is to produce a tabletop robot (a stationary robot torso with active vision and a grasping arm) that is able to manipulate items on a tabletop, communicate effectively with humans, and learn new behaviours through imitation.

Another major goal is to introduce imitatory behaviours into a society of cooperating autonomous robots, so that agents can communicate skills through imitation (Riekki & Kuniyoshi, in press).

The Development of Imitation

One of the critical problems in imitation is how an agent maps an *observed* action to the motor commands required to imitate it. As an example, if I wave my hands in front of a robot, how can it deduce the actions that it must take to produce a similar movement with its actuators? And what do we mean by 'similar' anyway?

If we take an analytical approach, it would appear that the robot needs to invoke a complex mapping function. Not only must it be able to deduce the correspondence between my body and its body, and my arm and its arm, it must also be able to map from its *registration* of the action (for example, a visual tracking of the moving arm) to the motor command sequence required to reproduce a similar action by its robot arm.

Such a mapping is non-trivial. It subsumes the inverse kinematics problem, where one must map from a stationary position of one's arm to the joint settings required to achieve that position. In this case, it's much harder: the robot needs to calculate a sequence of joint settings for its arm from observing (a sequence of) positions of the *teacher's* arm.

We plan to implement an imitating robot that achieves the same result using a much simpler strategy. Our approach is inspired by a psychological account of the cognitive strategies used by human children to *learn* how to imitate.

Imitation is not an innate behaviour; it must be learned. Children are at first unable to imitate at all, and can only imitate novel behaviours (with limited success) after the age of 12 months.

Piaget (1962) studied the development of imitation skills. His essential thesis was that imitation is composed of a set of simple mechanisms. These mechanisms interact with each other, and the environment, to produce a predictable stagewise progression in the child's ability to imitate.

Piaget's findings are curiously convergent with the recent 'animat' approach to robotics, that aims to implement complex emergent behaviour through the interaction of simple mechanisms.

Piaget's Imitation Mechanisms

Here, we give a brief overview of the mechanisms hypothesized by Piaget, and describe how they interact to produce imitatory behaviour. For a more detailed discussion of how these mechanisms cause progression through Piaget's stages of learning, see our recent report (Bakker, 1996a).

The major mechanisms underlying imitation are as follows (Piaget, 1962):

- Exploration
- Circular Reactions
- Assimilation
- Accommodation

Exploration is the initial play period in which the child explores the set of possible behaviours. Explorations will be limited by natural constraints and tempered by reflexes. For example, a child might flail her arms or say "ba" and "da". Using this mechanism, the child builds up a repertoire of actions, and *registrations* of those actions, from observing herself perform them.

Exploration provides the child with a set of base behaviours from which to draw on to *produce* imitatory behaviours, and a set of registrations with which to compare and *recognize* behaviours.

The mechanism of **Circular Reactions** profoundly shapes infant behaviour. The child is motivated to reproduce any act that it observes and recognizes; that is, any act that it has already discovered itself. For example, if the child hears someone say "ba", and it knows how to produce this sound, then it will repeat the utterance. This is also known as *conservative imitation* – the imitation of known behaviours.

Circular Reactions provide the child with the *motivation* to imitate. They even imitate themselves. This leads to the repetitive actions that are so typical of infant behaviour (e.g., repeating "ba ba ba", or banging a toy).

Assimilation is the process whereby the child maps an observed behaviour to the closest one she has seen before. If the child has a small repertoire of behaviours, the observation might be assimilated to one that seems quite different. For example, juggling is reproduced as ball throwing; or "lala" is reproduced as "dada".

Assimilation provides the child with a crude means of selecting an action to perform as a circular reaction. It is based purely on the observation of the outcome of an action, and not on any understanding of the process involved.

The mechanisms of exploration, circular reactions and assimilation are sufficient to allow the infant to reach stage 3 of development – where *conservative* imitation is performed with accuracy.

In stage 4, the step is made to 'true' imitation – the ability to learn novel behaviours through imitation. The trigger for this is the maturing mechanism of **Accommodation**: the ability to detect and correct the differences between an observed behaviour and one's own reproduction of it. For example, an adult says "barn" and the child responds with "bah". The development of a more discriminating representation of speech sounds allows the child to perceive the difference between these two utterances, and the mechanism of accommodation adjusts her speech act gradually until it fits the desired outcome. For example, the child might try "bah", "bag", "bahg", and finally "barn".

In the physical domain, a child might observe a teacher clicking his fingers. He tries tapping his fingers together – a known action – and experiments with adjusting his behaviour from there. Success is not guaranteed, and would depend on the level of skill so far attained, and the continued help and encouragement of the teacher.

Discussion

By pursuing the developmental route, we hope to solve one of the critical problems of imitation: how one maps a novel observed action to one's own body. It is assumed, in our model, that this cannot be done for a completely novel action: the observed action must first be mappable to one that the agent already knows, and then adapted stepwise from there. In other words, and conforming to the old adage, it is not possible to learn a *new* behaviour unless one *almost* knows it already.

Importantly, this teleological approach to behaviour induction is physically grounded in the first stage of learning, where the agent explores the space of possible behaviours allowed by its physical embodiment, and builds up a repertoire of behaviours.

A computational architecture for controlling the development of imitation has been specified along the lines sketched out above. As a first experiment, we are applying this control architecture to the learning of speech sounds by a robot. The agent is provided with hearing capabilities and an articulatory synthesizer (a model of the human vocal tract) with which to produce speech. It is allowed to explore its range of vocalizations, and store the resulting sounds. In interaction with a human teacher, the robot will engage in conservative imitation, eventually tailor its set of utterances (in the first instance, monosyllables) to the teacher's language, and by the fourth stage engage in true imitation of novel speech sounds. If successful, this will demonstrate for the first time a learning scheme that allows robots to learn truly *novel* behaviours (Brooks & Mataric, 1993).

Conclusion

Robot learning is a field full of promise, but fraught with intractable problems. *Imitation learning* offers a new approach that promises a richer environment for the learning robot, provides a simpler channel of communication between humans and robots, and may finally empower robots to induct novel behaviours. The aim of this paper has been to review both the promise and the problems of this burgeoning new field in robotics. While recent work is encouraging, there are still many deep problems in perception and representation to be addressed before general imitation learning will become a reality in robots. Recent work at ETL is drawing on insights from developmental psychology to address some of these problems in a practical way.

Acknowledgements

This work was generously supported by the Science and Technology Agency program of the Japanese government. Our ideas have benefited greatly from discussions with visitors and colleagues at ETL: Alex Zelinsky, Polly Pook, Luc Berthouze, and Jukka Riekki. Thanks also to John Demiris and Kerstin Dautenhahn for ongoing email contact and encouragement.

References

Bakker, P. (1996a). A description of a robotic progression through the first four developmental stages of imitation: Cognitive mechanisms. Manuscript in preparation.

Bakker, P. (1996b). Simple mechanisms for behaviour contagion in autonomous robots. Manuscript in preparation.

Brooks, R. A., & Mataric, M. J. (1993). Real robots, real learning problems. In J. H. Connell & S. Mahadevan (Eds.), *Robot Learning*, pp. 193–213. Boston, MA: Kluwer Academic.

Chesler, P. (1969). Maternal influence in learning by observation in kittens. *Science*, *166*, 901–903.

Dautenhahn, K. (1995). Getting to know each other – artificial social intelligence for autonomous robots. *Robotics and Autonomous Systems*, *16*, 333–356.

Drescher, G. L. (1991). *Made-Up Minds: A Constructivist Approach to Artificial Intelligence*. Cambridge, MA: MIT Press.

Galef, B. G. (1988). Imitation in animals: History, definition and interpretation of data from the psychological laboratory. In T. R. Zentall & B. G. Galef (Eds.), *Social Learning: Psychological and Biological Perspectives*, pp. 3–28. Hillsdale, NJ: Lawrence Erlbaum.

Hayes, G., & Demiris, J. (1994). A robot controller using learning by imitation. In A. Borkowski & J. L. Crowley (Eds.), *Proceedings of the 2nd International Symposium on Intelligent Robotic Systems*, pp. 198–204. Grenoble, France: LIFTA-IMAG.

Kuniyoshi, Y. (1994). The science of imitation – towards physically and socially grounded intelligence. Tech. Rep. RWC TR-94001, Real World Computing Project, Tsukuba-shi, Ibaraki-ken, Japan.

Kuniyoshi, Y., Inaba, M., & Inoue, H. (1994). Learning by watching: Extracting reusable task knowledge from visual observation of human performance. *IEEE Transactions on Robotics and Automation*, *10*(6), 799–822.

Maes, P. (1993). Behavior-based artificial intelligence. In J. A. Meyer, H. L. Roitblat, & S. W. Wilson (Eds.), *From Animals to Animats 2*, pp. 2–10. Cambridge, MA: MIT Press.

Piaget, J. (1962). *Play, Dreams and Imitation in Childhood*. New York: W. W. Norton. (Original work published 1945).

Riekki, J., & Kuniyoshi, Y. (in press). Behavior cooperation based on markers and weighted signals. To appear in *International Symposium on Robotics and Manufacturing*, Montpelier, France, May 1996.

Thorndike, E. L. (1911). *Animal Intelligence*. New York: Macmillan. Cited in Galef (1988).

Tsotsos, J. K. (1995). Behaviorist intelligence and the scaling problem. *Artificial Intelligence*, *75*(2), 135–160.

Yando, R., Seitz, V., & Zigler, E. (1978). *Imitation: A Developmental Perspective*. Hillsdale, NJ: Lawrence Erlbaum.