Towards Developing Behavior Based Control Architectures for Mobile Robots Using Simulated Behaviors

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Abstract

This paper proposes the Simulated Behaviors Approach for using simulation to investigate the structure and function of control architectures for behavior based mobile robots. The philosophical basis of the approach is discussed and a set of guiding principles are suggested. Finally, our progress is outlined and further lines of research are identified.

Keywords: Mobile Robots, Simulation, Behavior Based Control, Simulated Behaviors

1. Introduction

This paper is concerned with the design, development and investigation of control architectures for behavior based mobile robots [2] through the use of simulations. The use of simulation has the potential to save time and money in the robot development process, bring more resources to bear against the project objectives, facilitate research and lead to improved designs. While this paper is motivated by the development of control architectures by hand, other applications of simulation include robot design by the techniques of evolutionary computing [8], and research into embodied cognitive science [9]. Space prohibits a general discussion of the merits of robot simulation here, but one can be found in [5].

This paper will take the term 'behavior' to mean, *an observable and repeated pattern in the relationships among spatio-temporal events associated with an agent and its environment*. An agent will be taken as anything that has the ability to ascertain and cause events in its environment. These terms are intended to apply equally well to robots, animals, people, and even computer programs such as virtual organisms and soft-bots [4].

A discussion of emergent behavior is provided by [15], and a more concise description is given in [13]. In this paper the term *emergent* is used to refer to a behavior, the existence of which depends upon specific interactions between other behaviors of the same agent and/or other agents. It is implied therefore, that there must be some behaviors that can exist independently of other behaviors. Mataric coined the term "*basis behavior*" to refer to such behaviors, and used robots with behavior based control architectures to study the use of basis behaviors as building blocks for synthesizing and analyzing complex group behavior in multi-agent systems [14][13]. In this paper, the same idea is employed only the means has become the ends: we suggest the use of simulated behaviors at a lower functional granularity to study control architectures on a single agent. In order to separate this unproven approach from the work by Mataric, we use the term "*base behavior*" rather than basis behavior.

2. Philosophical Issues

It is worth remaining circumspect and asking whether there are any fundamental obstacles to the success of efforts to simulate behavior based mobile robots that should be kept in mind from the outset.

In [6], and also partly in [3] and [7], Brooks describes the key ideas of situatedness, embodiment, physical grounding and emergent behavior as important characteristics of a behavior-based mobile robot. The field of behavior based robotics is further described in [12], and [16]. Before attempting to simulate such robots it should be asked whether it is even possible for these key characteristics to be honored by a simulation. Essentially, this is the same as asking if it is possible for these characteristics to be honored by a software or 'virtual' agent.

2.1. Situatedness

The situatedness of behavior based robots has been characterized as referring to all of the following ideas: "The robots are situated in the real world – they do not deal with abstract descriptions, but the here and now of the environment which directly influences the behavior of the system.” [6][10]. “….predictability and stability of environment have a direct impact on the complexity of the agent that must exist in it” [1]. “A situated agent must respond in a timely fashion to its inputs” [6]. “The world is its own best model… an agent uses its perceptions of the world instead of an objective world model” [6]. ”(The world) is always exactly up to date. It always contains every detail there is to be known.” [7].

Apart from existing “in the real world”, there is nothing in the preceding paragraph that cannot be equally true of a virtual agent, and this position is well argued by Etzioni in [4]. Further evidence of this viewpoint can be found in [17]. The significance of the real world to situatedness would seem to be that an *agent* in the real world, such as a mobile robot, is inevitably subject to all of the above conditions[1], whereas a virtual agent may be subject to only some subset of them depending on the particular implementation of that agent and its environment. The important point here for efforts at simulation is that care must be taken to ensure that these conditions are indeed met by our particular implementation.

2.2. Embodiment

Embodiment refers to the significance of an agent having a body. How this significance should be understood is a matter of ongoing discussion. One position already considers it possible for a virtual agent to be embodied: “Embodiment is a type of situatedness… having a physical body and thus interacting with the environment through the constraints of that body… Physical robots are embodied, as are simulations whose behavior is constrained and affected by (models of) physical laws.” [1]. Several different types of embodiment, and the extent to which they apply to robots and virtual agents are defined and discussed in [18], [19] and [20], which provide a good overview of the ideas involved. An ontologically independent definition of embodiment is suggested in [11], which emphasizes the importance of structural coupling between a system and its environment.

In the context of a behavior based mobile robot, structural coupling is well expressed as follows: “The robots have bodies and experience the world directly – their actions are part of a dynamic with the world, and their actions have immediate feedback on the robots’ own sensations.” [6]. This structural coupling will be taken as the aspect of embodiment that must be honored in simulation. It is interesting to note that while Brooks was actually advocating the importance of a *physical* body in the *real* world, neither of these words appear in the quotation just cited, which, it is felt here, applies equally well to virtual worlds and bodies as to real ones (with the substitution of ‘agent’ for ‘robot’). Support for this position can be found in [4] and [11].

2.3. Physical Grounding

Having conveniently side-stepped the issue of having a real physical body in the contexts of situatedness and embodiment, it must now be met head on. One of the key reasons Brooks advocates the importance of *physical* embodiment is expressed in his Physical Grounding Hypothesis: “… to build a system that is intelligent it is necessary to have its representations grounded in the physical world.” [7]. With regards to physical embodiment Brooks explains: “Only through a physical grounding can any internal symbolic or other system find a place to bottom out, and give ‘meaning’ to the processing going on within the system…. The world grounds (the) regress (of meaning giving)” [6]. As to how this grounding is performed for a mobile robot, Brooks says “…it is necessary to connect it to the world via a set of sensors and actuators.” [7].

There is an implication in the Physical Grounding Hypothesis that the information a real robot gleans from its environment through its sensors is somehow more meaningful than the information a virtual agent could glean from its virtual environment through virtual sensors. This implication is disputed here. Any sensor, be it real or virtual, produces an abstraction of some aspect of the environment. How such abstractions are ultimately represented and operated against within the agent is beside the point when it comes to evaluating the meaning of the abstraction itself. While we agree that the only meaningful abstractions for a real robot are those made from its real environment using its own real sensors, we further suggest that the only meaningful abstractions for a virtual agent are those made from its virtual environment using its own virtual sensors. As such, both the real robot and virtual agent may be equally well “grounded” in their own real and virtual realities respectively. Again, this position is very similar to that of Etzioni in [4].

2.4. Validity of Simulation

While it is claimed here that there is no reason in principle why a virtual or simulated agent cannot be every bit as situated, embodied and grounded in its world as a real robot, it is not implied that this is an

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[1] This is unsurprising since the idea of situatedness was originally derived by considering agents in the real world.

easy thing to achieve. Nor is this claim intended to dismiss concerns about the validity of simulating real robots. However, it is felt that such concerns are really getting at something different. Specifically, when it is claimed that a virtual environment in which a virtual agent is situated, embodied and grounded, is such a good model of a real environment in which a real robot is situated, embodied and grounded, that experimental results in the virtual system should be expected to carry over to the real system.

It should be asked whether such a good model is even possible. Fortunately, as described in [11], the field of evolutionary robotics has already provided an answer in the affirmative. Quick goes on to suggest the following axiom: "Where behavior emerges from the interplay between system and environment, if exactly the same system-environment relationship is instantiated in two cases then the same characteristic behaviors are seen to emerge". This axiom corresponds to preserving the spatio-temporal relationships between an agent and its environment.

Of course there is also plenty of anecdotal evidence about attempts to simulate real robots that have failed to be useful, which may have fueled the idea that such attempts are futile and led researchers to postulate reasons why: the simulated robot cannot be embodied, for example. Why then do some attempts succeed and others fail? This is surely an important question to ask before embarking on any such attempt. Moreover, the modeling process bears closer examination.

2.5. Making The Right Abstractions

In order to design a virtual environment and an inhabiting agent that models an existing real environment and robot, it is necessary to make a great many abstractions about the real system. Clearly, the real system contains a far greater complexity of information and physical laws than could ever be entirely reproduced in a computer simulation. So, it is necessary to identify all aspects of the real system that are *relevant* to the subset of that system's behaviors which will be modeled by the virtual system. Key questions include - what are the behaviors of interest? what must happen in the real system in order that those behaviors are seen to emerge? and in particular, on what abstractions of the real environment is the agent operating? This first step is exactly the same as the first step that must have been performed when the robot itself was designed. The robot may exist in a world that "always contains every detail there is to be known", but it is only ever privy to the tiny fraction of that information that its designers deemed necessary when they selected its sensors. Although the robot engineer does not have to build the environment, and the simulation engineer does, both must make the same set of abstractions about that environment first. Consequently, designing a robot is subject to the same problem of making the right abstractions as arises when building a simulation of that robot.

However, the consequences of mistakes in this process are different for simulation than for the real robot. For the real robot, erroneous or incomplete abstractions on the part of its designer lead to a failure to achieve the desired behaviors i.e. the robot doesn't work, or if it does, it may not be for quite the same reasons its designers anticipated. In contrast, since the simulation is a simplification of reality, it may still appear to achieve the desired behaviors, but the results obtained do not transfer to the real system i.e. the simulation is not useful. It would seem unfair to criticize simulation on the grounds that some simulations are not useful, when some robots do not work for much the same reasons. Moreover, any comparison of these different consequences should be on the basis of the cost to remedy them.

In either case, there is no formal systematic way to ensure correctness from the outset and it comes down to the individual insight and aptitude of the researcher to make the right abstractions. Taken together with the fact that not all simulation problems are of equal difficulty, this readily answers the question of why some attempts succeed and others fail. Of course, actually building a robot and building a simulation do require different skill sets, and this further complicates the picture.

2.6. Evaluating the Model

So when results do transfer successfully from simulation to reality, does this mean that the model is perfect? No, merely that it is good enough for the purposes at hand in that at least a bare minimum of abstractions have been correctly made and well implemented by the simulation designers. Moreover, for other purposes the model may fail completely, but whether or not anyone should care about this is a matter of perspective.

An obvious question is: if the only way to validate a simulation is to compare its behavior with the real system being modeled, which requires that the real system be built, why spend time developing the simulation? The answer is that some experiments may still be faster and cheaper to perform on a validated simulation, or, as is the case with some examples of evolutionary robotics, impossible to perform with real robot hardware. In section 3, an approach to robot simulation is proposed that does not depend on the simulation being validated against a real system.

3. The Simulated Behaviors Approach

It was noted in the previous section that in order to prove the accuracy of a simulation it is necessary to compare its behavior to that of the real system being modeled. On what basis is this comparison made? Is there some formal systematic way in which the behavior of any two systems can be independently described so that no doubt remains in the evaluation of whether or not they are the same? We are not aware of such a methodology at this time, and in general it will be down to the each researcher to determine a means of behavioral comparison that is appropriate for the particular problem at hand. For an example see [14]. The idea of developing a general approach to behavioral specification is intriguing, but unfortunately it cannot be addressed within the bounds of this paper.

The same questions regarding behavioral specification should be asked of endeavors to build behavior based robots even if no simulation will be attempted. Ultimately, it is just such a specification of what the robot is supposed to do that determines the design decisions.

Regardless of the way in which a behavioral specification is expressed, an idea of the desired behavior necessarily precedes the process of abstraction for both designing a robot and designing a simulation of that robot. We ask here if there is any aspect of the robot that can be investigated using a behavioral specification alone, i.e. without building the robot as well. If the behavioral specification refers only to the overall observed behavior of the finished robot as it operates within its environment then the answer is no. However, this is not the case for a behavior based robot whose initial design has been specified in terms of multiple parallel base behaviors that operate simultaneously and combine to produce emergent behaviors. For such a robot, an additional system is required to perform ‘arbitration’, that is to coordinate the base behaviors. Whether the form of the additional system is regarded as simply a set of interconnections between the sub-systems responsible for the base behaviors, or an additional behavior itself, or a higher level independent ‘executive controller’, it will be described here as the control architecture.

The function of the control architecture is inextricably linked to the ways in which the base behaviors can be influenced by inputs to their respective sub-systems. The ‘ways’ and ‘inputs’ can be viewed as behavior control functions or interfaces to each base behavior that could be specified in the same terms as the base behaviors themselves. This amounts to parametizing the behavioral specifications and providing a control input for each parameter. The simplest example is an on/off input parameter which allows inhibition and sequencing of otherwise concurrent behaviors. For a behavior at quite a high level of granularity like wall-following, an example parameter might be the distance from the wall.

The behavior interfaces can be considered as the beginnings of the control architecture. To complete the control architecture the behaviors must be connected through their interfaces either to each other or via additional systems. The details of the eventual physical implementation of the base behaviors and any connecting systems are not under consideration. What is of interest here is the structure of the interconnections, the meaning of the signals carried, and the resulting overall function performed in terms of behavior coordination. The inner workings of the base behaviors are hidden from the control architecture (as in [14]), which, to some extent, is then desensitized to the particular abstractions of the robot’s environment on which the base behaviors operate.

Recall now the definition of a behavior given in section 1: the definition implies no distinction between a base behavior of a real robot and a base behavior of a simulated robot as long as the important spatio-temporal relationships among events are preserved. If, in this way, the corresponding real and simulated base behaviors adhere to a common behavioral specification, then the required overall function of the control architecture should be the same in both the real and simulated case. Given such a specification of the base behaviors and the function of their control interfaces, it would seem possible to investigate the required function of the control architecture in simulation without constructing the real robot. Of course, this position supposes that the same behavioral specification would be rigorously applied to the base behaviors of any real robot (constructed later) to which the findings of the simulation were intended to be relevant. This approach has not yet been proven, but it is the subject of ongoing work.

Even if no real robot were ever constructed, it would still seem that there is something to be learned about control architectures by following the simulated behaviors approach. Consider the suggestion that as a result of designing and building behavior based agent A, insight was gained that proved helpful when designing and building behavior based agents B and C with the same control architecture. If agent A is a wheeled differential drive robot, agent B is a wheeled robot capable of holonomic motion, and agent C is a robot that walks like an insect, then the original suggestion sounds reasonable. What if agent A is actually a faithful and fully validated simulation of the differential drive robot? Lastly, consider that agent A is actually a simulation of the base behaviors of the same, but now hypothetical, differential drive robot and the insights claimed are limited to the structure and function of the control architecture only, and not the details of any physical implementation.

There are a few caveats about the simulated behavior approach that are worth stating.

i. **Beware of Imitations** - The definition of a behavior that has been used does require the involvement of an agent with the ability to ascertain and cause events. Consider a simulation of a wall-following robot in which a representation of the robot is seen to follow a representation of the wall in observably the same way, but only because it is following a pre-programmed path without sensing the wall. Such an imitation does not fit the definition of a behavior and so is not a simulated behavior in the intended sense.

ii. **Identical overall behavior is not required** - Suggesting that the required function of the control architecture for a real robot and for a simulation of that real robot's base behaviors should be the same, is not the same thing as saying that the resulting emergent behavior should be absolutely identical in both cases. Moreover, it is generally unlikely that any mobile robot simulation should behave identically to the system it models, and further it is not felt that such identical overall behavior is necessary for the simulation to be useful. It is hoped, however, that any differences in overall behavior that do emerge would come down to a matter of scalar parameters, and not a difference in fundamental structure, control functions or achievable behaviors.

iii. **Feasible and unfeasible behaviors** - One advantage of using simulated base behaviors is that the control architecture is isolated from the inner workings of each base behavior. It then becomes possible to capitalize on some simplifications of reality that would otherwise ruin simulation validity. In particular, the availability of perfect sensor data makes it far easier to implement certain base behaviors in simulation than it is on a real robot where issues of noise and resolution cause significant complications. Taken far enough, this could lead to a simulated behavior that is actually unfeasible to implement in the real world. Care must be taken to evaluate the feasibility of any simulated base behavior by comparing it with behaviors known to have been implemented successfully on real robots. If insight into control architectures on currently realizable robots is expected, only feasible behaviors can be simulated. On the other hand, an intriguing possibility presents itself. The investigation of control architectures can be freed of the constraints imposed by limitations of current robot hardware. Such investigations could provide motivation for directions to push sensor and actuator technology.

In summary, the key idea of the approach is to simulate behaviors, not real robots, with each behavior having a control interface via which it can be integrated into a behavior control architecture. The approach rests on the condition that as long as each base behavior is properly specified and modeled, and as long as the simulated behaviors meet the same defining criteria for being "a behavior" as can be used for real robots, then although the mechanisms that give rise to each base behavior are different depending on the system - be it physical robot A, physical robot B or simulation C (or even life-form D), the function of the control architecture required to achieve target emergent behavior should be the same, or at least sufficiently similar such that work on it in simulation bears utility for the real world.

Obviously, such simulations tell us nothing about sensor/actuator issues because no attempt is being made to model real ones. Essentially, this is an attempt to take advantage of the oft criticized fact that simulation can side step numerous real world issues at the sensor/actuator level, by purposefully side-stepping said issues (saving a lot of time in the process) in such a way that it does not matter for the objectives of the simulation. These simulations will not try to provide a development platform for code that can be reused on real robots. Instead they will try to gain insight into the function and logical design of control architectures in a way that is independent of their eventual physical implementation in the real world, which could be anything: hard-wired solid-state logic circuits, single processor embedded micro-controller, parallel multi-processors, and analogue circuits to name a few.

4. Principles for Validity

These principles do not represent an exhaustive list: they are the ideas distilled from an ongoing piece of work. For a general discussion of principles for implementing robot simulators see [5].

1) Space should be represented and managed such that
    a) Dimensions are to scale with the real world.
    b) The continuous nature of space is preserved or approximated at an arbitrary level of resolution that should be chosen to be very much smaller than any distances of interest.
    c) No point in space may be occupied by more than one thing simultaneously.
    d) Agents can be embodied in the sense of structural coupling as discussed in section 2.2
    e) Agents can be situated as discussed in section 2.1
    f) Agents are all equally subject to a set of physical laws regardless of processing load on the simulation.
    g) Behaviors can be observed in the same way (visually) as they could be in the real environment.
    h) Agents can be grounded in that all information on which a behavior operates internally is an abstraction of some aspect of the representation of the environment (including the agent's representation), or derives from such abstractions via other behaviors.

2) Time should be represented and managed such that
    a) Simulated time proceeds independently of any behavior.
    b) The continuous nature of time is preserved or approximated at an arbitrary level of resolution that should be chosen to be much smaller than any time intervals of interest.
    c) Relationships in simulated time are preserved independently of the amount of real time taken by the simulation to perform its processing.
    d) Any number of behaviors may be active simultaneously without causing a distortion of spatio-temporal relationships due to processing load on the simulation.
    e) The opportunity to interact with the environment afforded to a behavior is proportional to its response time and not the time taken for the simulation to perform processing associated with the environment.
    f) The response time of a behavior may be treated as being different from the time taken for the simulation to perform processing on behalf of that behavior.
    g) The relative orders of magnitude of the time taken for an agent to move a percentage of its body length, and the response times of the behaviors involved, are the same in simulated time as they are in the real world.

5. Ongoing Work

A crude but working prototype of a 2D mobile robot simulator has been developed and used as a test-bed to investigate techniques for implementing the principles for validity outlined in section 4. The principles associated with space (1 a - h) were all implemented with varying degrees of success. However, the prototype exhibited no success with all but the first of the principles associated with time (1 a). Consequently, the prototype is not felt to be up to the task of investigating control architectures, and only single, serial behaviors at a coarse level of granularity have been implemented and tested.

Despite these shortcomings, a number of simulated agents equipped with only a simple 'bump' detection capability did exhibit some interesting emergent behavior. Specifically, despite having sufficient maneuverability to cover the whole environment, a rectangular agent with a differential drive steering geometry was seen to get stuck against a wall from time to time in areas where its 'back up and turn' behavior was too simple to reliably cope with its surroundings. Another agent, circular in shape and capable of holonomic movement, was seen to effectively explore the entire environment without ever getting stuck while executing only a 'move at random' behavior. While watching these agents, the similarity between their behavior and that which would reasonably be expected of their real counterparts was quite striking, and provides a source of encouragement.

Multiple lines of work would be beneficial to this project:

1) Research into more rigorous and systematic approaches for
    a) Making the right abstractions when modeling a behavior based robot and its environment.
    b) Specifying behaviors and behavior control interfaces.
2) Find or build a simulator that meets the principles for validity outlined in section 4.
3) The simulator should be used to model a number of base behaviors at a low level of granularity for a single agent so that control architectures can be investigated in simulation.
4) An attempt should be made to transfer a control architecture developed in simulation to a real robot that implements the base behaviors as they were specified for the simulation.

6. Conclusions

This project has only just begun and certainly has a long way to go before any of the hopes and claims made here about the simulated behavior approach can be substantiated. In this paper, the motivation, philosophical position and direction of the project have been set out. Initial prototyping and experiments have provided some encouragement along with insight into the technical challenges that lie ahead, and multiple lines of work have been suggested.

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