Hierarchical and State-based Architectures for Robot Behavior Planning and Control

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Abstract—In this paper, two behavior control architectures for autonomous agents in the form of cross-platform C++ frameworks are presented, the State Controller Library and the Behavior Control Framework. While the former is state-based and generalizes the notion of states and finite state machines to allow for multi-action planning, the latter is behavior-based and exploits a hierarchical structure and the concept of inhibitions to allow for dynamic transitioning. The two frameworks have completely independent implementations, but can be used effectively in tandem to solve behavior control problems on all levels of granularity. Both frameworks have been used to control the NimbRo-OP, a humanoid soccer robot developed by team NimbRo of the University of Bonn.

I. INTRODUCTION

The programming of complex agent behaviors that are intended to function in highly dynamic environments can be a challenging task in modern robotics. Without the support and uniformity of a well-defined behavior control architecture, this task can be even harder. Two such behavior control architectures, implemented as cross-platform C++ frameworks, are presented in this paper and proposed for use. These are the State Controller Library (SC Library) and the Behavior Control Framework (BC Framework).

An agent system with clearly defined inputs and outputs is considered, one that at every instant must select its output action(s) based on its signal inputs. These signals may involve sensory inputs that quantify characteristics of the environment, and/or signals directly from external sources or other agents. This action selection process is referred to as the *behavior control* problem, where a behavior is taken to be an observable and coordinated pattern of activity of an agent, involving action and/or response to stimuli from the environment [1]. Every robotic agent requires some form of architecture for behavior control in order to complete the tasks that it is given. Simple reactive feedback control loops have been used since the earlier days of robotics with much success, but with the increasing complexity of tasks and capabilities of robotic systems, these have grown insufficient to be a complete solution for applications such as robot soccer and domestic service robotics.

The challenge is to find an efficient and modular way of representing and programmatically implementing complex behavioral systems in code, ideally in the form of a library or framework. Any such construct needs to facilitate the implementation and encapsulation of near-arbitrary control systems, capable of dealing with real-world effects such as disturbances, sensor noise, environment stochasticity, and partial controllability and/or observability. These are conditions for which traditional artificial intelligence (AI) architectures were generally not designed to handle, with simplified and abstracted virtual environments being more typical platforms for the development of AI than the highly dynamic environments generally encountered by autonomous mobile agents. A trivial example of this would be the observation that, while an agent that simply uses a predetermined sequence of actions for its behavior may be consistently successful in a structured and deterministic software environment, a similarly controlled robot would likely fail whenever any of the aforementioned real-world conditions come into play. In addition to the efficiency and modularity requirements of a behavior framework, it is also desirable for such a framework to inherently support the notion of planning into the future, as opposed to focusing on purely reactive control. This is specifically addressed by the SC Library, as described later in Section III.

Both frameworks were designed, implemented, utilized and tested within the setting of humanoid robot soccer. As opposed to being mutually exclusive for an application, these two frameworks were written in a way that they can easily and effectively be used in tandem. The NimbRo-OP robot [2], developed by team NimbRo of the University of Bonn, was used as a testbed. The NimbRo-OP is a humanoid platform that is open source, both in terms of its hardware and software. As such, the SC Library and the BC Framework are available as part of the NimbRo Robot Operating System (ROS) soccer package software release for the NimbRo-OP. It is to be noted however that despite their origins in the area of humanoid robot soccer, the frameworks were written to be completely generic, allowing them to be used in virtually any type of robotic system—or even software system—that requires some notion of behavior control. Nevertheless, in a broad sense, the two frameworks are targeted for use in real-time systems. The NimbRo-OP currently makes use of the BC Framework for its soccer behaviors.

II. RELATED WORK

As behavior control is one of the fundamental problems in the field of robotics, many approaches have been developed in the past. Behavior control has been heavily researched within the context of artificial intelligence [3]. This has led to a number of architectures and classical artificial intelligence approaches. These were generally developed within the setting of simplified virtual environments however, and so were not designed for use on robots in highly dynamic real-world environments, with all the nonidealities that come with it. An example of such an architecture is the Belief, Desire and Intention (BDI) agent model [4], [5]. This model is based on modal logics and the partial or complete axiomatization

thereof. Multiple BDI logic variants exist, but all of them in general include modalities for beliefs, desires, intentions, capabilities, actions, agency, and time [6]. A strength of the BDI logics is their strong formalization and theoretical foundations, but it is a non-trivial task to apply such logics to describe and control robots in real-world applications [7].

Earlier approaches to behavior control from the field of robotics include the *subsumption architecture*, a behavior-based approach. This was originally proposed by Brooks in [8], but was later modified in [9] and [10]. The idea of the subsumption architecture is to arrange the behaviors in a layer hierarchy where higher layers can influence and suppress the data flow of lower layers in order to achieve higher-level goals. Brooks constructed a number of robots to demonstrate the architecture, leading in particular to robots with insect-level behavior and intelligence [11], [12]. Adaptation of the architecture to more complex systems proved to be difficult.

Maes developed the Agent Network Architecture (ANA) [12], [13], also a behavior-based artificial intelligence approach. In this architecture, the agent consists of a distributed and decentralized collection of primitive behaviors, referred to as *competence modules*. The competence modules are divided into groups of incompatible behaviors, and interact based on a network of predecessor, successor and conflictor links in such a way that the various modules are activated and inhibited dynamically when appropriate. Each competence module only implements a single basic primitive behavior however, so the activation network would grow quite large for real-size problems and become slow and overwhelmed by details [12]. Also, it is a difficult task to tune all of the network parameters and activation functions so that the appropriate module(s) for a given situation in general tend to be activated.

In a different category to the previously mentioned approaches to behavior control are the class of behavior control languages—languages that were specifically designed for the specification of behaviors, usually on a rather conceptual level. Examples include the Behavior Language by Brooks [14], which was based on [10] and his prior work on the subsumption architecture, the Configuration Description Language [15], and Colbert [16], part of the Saphira Control Architecture [17]. A more recent example of a behavior control language is the *Extensible Agent Behavior Specification Language (XABSL)*. Originally developed in [18] as an XML-based language, it has been extended and improved incrementally in works such as [19], which introduced a behavior language representation for XABSL with a more compact syntax. The idea behind XABSL is to use a hierarchy of finite state machines called *options* to select the appropriate action(s) to execute from a set of basic behaviors. XABSL currently finds relatively widespread use in humanoid soccer.

Behavior languages in general excel at abstracting away coding particularities of more generic low-level programming languages such as C++, allowing the main focus of behavior coding to remain more on 'what' rather than 'how'. This also generally allows more succinct representations of behaviors, or the interactions between them, to be constructed. The main disadvantage of using a behavior language is the overhead of coupling two different programming languages together, in terms of both project architecture and runtime considerations. A runtime engine is often required to execute the resulting
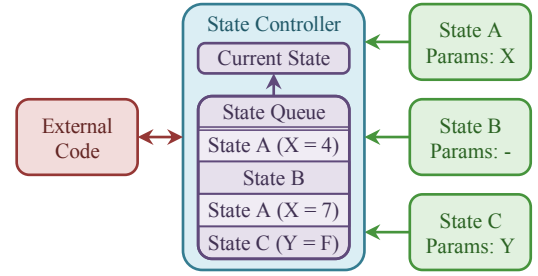

Fig. 1. A block diagram of the SC Library architecture with three sample states and a populated state queue.

behaviors and integrate them with the remaining code, which is not as efficient as behavior implementations that are seamlessly integrated using the one target language. The interfacing of data signals between the two languages can also be a challenge, often limiting the flexibility of such behavior control approaches. Neither of the frameworks presented in this paper is a language in its own right.

The next category of behavior control architectures are the state-based techniques. An example is the hierarchical control structure for mobile agents proposed in [20]. As the behaviors of a robot under development often grow incrementally from rather simple beginnings, it is not uncommon for a behavior control system to consist simply of a custom implementation of a finite state machine. When this becomes too cumbersome, or is otherwise not desired, many finite state machine code libraries exist that can be used to implement such basic state-based approaches (e.g. [21]). To the knowledge of the authors however, no other simple state machine implementation exists that allows for the planning of multiple future states as the State Controller Library presented in this paper does. This was a feature that was considered to be important for flexibility and extensibility reasons.

III.   THE STATE CONTROLLER LIBRARY

A. Overview

The State Controller Library is a generic platform independent C++ framework that allows finite state machines, hierarchical state machines, and multi-action planning generalizations thereof to be realized. The structure and implementation of the library focuses on the application of such architectural constructs to real-time control loops, but can be reasonably adapted for virtually any other application, even completely unrelated to control systems. While the underlying ideas and structure of the SC Library are of predominant interest here, it is worth noting that the simplicity of this behavior control approach allows for a very lightweight, unintrusive and resource-efficient implementation.

The core idea of the library is to have a state controller object with a certain collection of state object types that are bound to it. These state object types (i.e. classes in C++) are henceforth simply referred to as the *states* of the controller. Instantiations of a state are referred to as instances of that state, or *state instances*. These instances are executed by the state controller in the required order, as stipulated by a dynamically maintained list of desired future states. This list, which is

embedded inside the corresponding state controller, is referred to as the *state queue*. Each state is responsible at runtime for specifying its own outgoing state transitions by modifying this state queue. Although it is not necessary for an application to use the full flexibility of the queue—there are abstractions available in the SC Library that hide away the details of the queue if only simple functionality is required—it is still available at little to no performance cost. This increases the extensibility of control systems implemented using the library, and caters for applications where some form of action planning is desired. An overview of the SC Library architecture is shown in Figure 1. The latest release of the library as at September 2013 is version 1.2, and is available for download from the project page [22], where all future releases will also be made available.

B. Motivation

The conception of the State Controller Library was driven by two main considerations. The first was the need for a simple first solution to the behavior control problem for the NimbRo-OP robot. When the NimbRo-OP platform was first being programmed with basic soccer skills, a simple state machine framework was required to write the behaviors, pending a more powerful and long-term solution. In anticipation of the creation of the more powerful behavior control framework however, it was a second core consideration that the SC Library be able to be used to implement finite state machines within the individual behaviors of the future framework (i.e. the BC Framework). This would be for the case that an individual behavior requires a notion of sequentiality and state that is best implemented locally. An example of this is a walking or kicking behavior that uses different states internally for the different phases of the corresponding motion. As such it was important that the SC Library be able to be used for applications ranging all the way from the implementation of a whole soccer behavior system, down to the implementation of the smallest and most fundamental finite state machines in the code—without incurring any unnecessary overhead or performance losses. The performance and efficiency of the library was of particular importance due to the real-time nature of the NimbRo-OP control task.

Further attributes that were desired of the SC Library were for it to be robust to incorrect use, able to plan multiple actions into the future, and able to integrate seamlessly with the target code of the NimbRo-OP. The structure of the implementation was also desired to be control-based, not event-based. No existing state machine library was found that addressed all of the requirements outlined in this section.

C. Library Structure

The State Controller Library is written in C++, so it is able to make use of the object-oriented programming paradigm to break down the state control structure into a collection of objects. As previously indicated, the main objects in use are the *state controller*, the *state queue*, and the individual *state instances*. These terms were carefully defined in Section III-A.

At the core of the SC Library is a step routine that controls the execution of the state controller. The routine may be called continuously or at arbitrary intervals, but the intended use for control applications is for it to be called from a timed loop running at some nominal rate. Each step executes one so-called cycle of the state controller. In each cycle, it is first checked whether the currently executing state instance has set a flag in the last cycle that it has completed its task. If so, the state instance sitting at the head of the state queue is popped from the queue, activated and executed. If this state instance also completes its task some number of cycles later, during which time it is executed once per step, it is deactivated before the successor state is activated. Users of the library have the option to write specific code to handle the activation and deactivation events of the individual states. Once a state instance has been deactivated, it is marked as complete and can never be executed again. To reenter a previous state, a new instance of that state simply needs to be created and placed into the queue, as normal. Callbacks are made available to the user at all the stages of the main loop so that application specific code can be injected as necessary.

The motivation behind having individual state instances intended for single use only is so that multiple instances of a state can exist concurrently within the state queue, and so that the various state instances can be individually configured via *state parameters*. These are parameters that are passed to a state instance at construction time, and are used to specialize the task of a particular instance. For example, if a state has the task of bringing a robot to a particular global pose, then the state parameters can be used to specify the target global pose for a particular state instance. The power of this method is that multiple instances of a state within the queue can have differing customized objectives. To achieve even comparable results, standard finite state machines would somehow have to keep track at all times of where in a desired sequence of actions the currently executing state fits in, and modify the state objectives locally. This is not only more complex and error-prone to implement, but it also forces lower-level states such as locomotion states to be imparted with knowledge of higher-level goals.

D. State Transitions and the State Queue

Each state instance when it executes is responsible for modifying the state queue, the dynamically manipulatable ordered list of states that are pending execution by the state controller. As would generally occur when there are multiple items in the queue though, a state is not actually obliged to modify it. This allows low-level behavior states to be implemented (such as for locomotion) that do not need to deal with any knowledge of higher-level planning, as they do not need to specify their successor state. The successor state is already uniquely determined as the state that was previously placed at the head of the queue. As such, the higher-level planning can naturally be separated from the lower-level states that actually execute the plans, reducing the code complexity and clarifying its programmatic and behavioral intent compared to what would be expected with more traditional finite state machine implementations. It is important to note however, that an agent is still not committed to a plan once it has been pushed into the state queue. The queue can still be modified at any time by clearing, inserting, removing, rearranging, etc. the states as required, which can be necessary if significant changes in the environment are perceived.
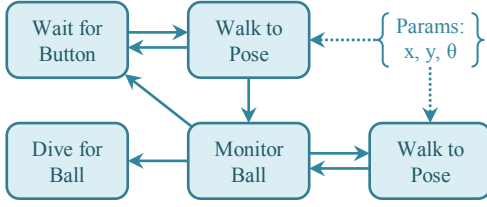
Fig. 2. A simplified example of a goalie behavior using the SC Library. Boxes represent the state instances, and the arrows indicate the possible transitions between them. The *Walk to Pose* state has three state parameters.
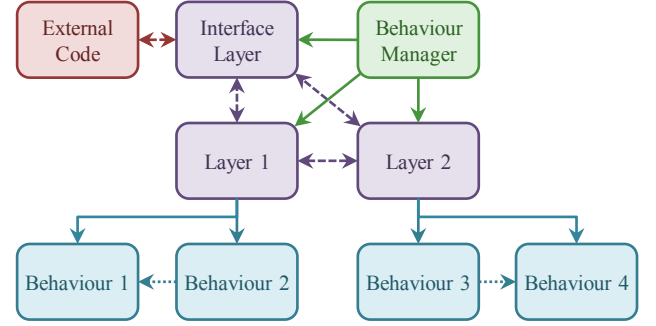

Fig. 3. A block diagram of the BC Framework architecture. Solid arrows indicate the object hierarchy, dashed arrows indicate the data exchange interfaces, and dotted arrows indicate sample inhibitions.

For smaller applications of the SC Library, pure simple next-state logic can be achieved by configuring the individual state instances to only ever add a single item to the end of the state queue, guaranteeing that this item will be at the head of the queue and the one and only successor state. Convenient shortcuts for this common operation exist within the library. In larger applications of the SC Library where the number of possible transitions grows quadratically with the number of states, it often occurs that certain groups of states have a collection of similar outgoing transitions, activated on similar preconditions. To avoid unnecessary code duplication, generic transition routines can be embedded inside the state controller object to apply the appropriate collection of outgoing transitions to multiple states at a time. Taking the idea of grouping the states a step further leads to a natural extension of the SC Library—if a parent state controller is used to selectively switch between a set of subordinate state controllers that each implement one of the groups of the original states, then a hierarchical state machine structure like the one in [20] emerges. It is then possible to go even further and take advantage of the state queues embedded in each of the subordinate controllers, allowing for even greater flexibility.

A fundamental difference between the SC Library and a large proportion of the other state machine libraries that already exist is that no explicit definition of a transition map or transition table is required in the code. An example of an entry in such a transition table would be a rule specifying that the combination of a certain event occurring in a certain state should cause a transition to a particular successor state. When employing simple next-state logic using the SC Library, this is encapsulated in the executed target code of a state, when a transition to another state is triggered from within a conditional expression. The 'event' in this case would be the change of the evaluation of the conditional expression from false to true. No direct analog of a transition table exists however when the state transitions come about due to the sequencing of multiple states in the state queue (although this is still equivalently performed by each of the individual state instances). This is regarded as a feature though, as it allows for more flexible and dynamic transitioning behavior, often desired in real-world applications.

E. Example

Due to the large number of states and possible transitions in a typical behavior control system, a complete example for a humanoid soccer behavior controller is not given here. Consider however the simplified goalie behavior controller presented in Figure 2. The goalie starts at the sidelines and must wait for a button press before it starts walking to its designated position in the goal. It then monitors the location of the ball based on its visual detections and can decide to dive at any time to protect the goal. While the goalie is keeping track of the ball, it may also decide to walk to a better defensive position within the goal area, before continuing to monitor the ball. The two instances of the *Walk to Pose* state have been kept separate in the diagram as a conceptually different task is being performed in each case, despite being the same underlying state. Also, as indicated in the figure, the *Walk to Pose* state has three state parameters, which are used to specify the target pose of the robot.

When the robot is started and the state controller is initialized, three states would immediately be pushed into the queue, *Wait for Button*, *Walk to Pose* and *Monitor Ball*. This has the effect that *Walk to Pose* does not need to specify, or even know, that its desired successor state in this case is *Monitor Ball*, and allows for a simpler and clearer implementation of the behavior. Once in the monitoring state, if the goalie decides to walk to a better location, it would enqueue a *Walk to Pose* state, followed by another instance of the *Monitor Ball* state, and mark the current state instance as being complete. This would once again relieve the *Walk to Pose* state of needing to know for what particular purpose, or as part of what plan, it was called upon. It is emphasized however that the goalie can still clear the queue and repopulate it at any time if the enqueued states are no longer appropriate. For example, if the button is pressed while the goalie is still walking out to its desired field position, the future monitoring state can be cleared from the queue and replaced with an instance of the *Wait for Button* state. The use of a state queue would also be advantageous if for example a fixed obstacle was detected on the way to the goal area. The robot would be able to dynamically prepend extra *Walk to Pose* states to the front of the queue in order to avoid the obstacle, all the while not 'forgetting' the desired successor state on arrival in the goal area, as an instance of *Monitor Ball* is still at the back of the queue.

IV. THE BEHAVIOR CONTROL FRAMEWORK

A. Overview

The Behavior Control Framework [23] is a generic platform independent C++ framework designed for behavior control on robotic platforms. It is intended for the implementation of mid- to high complexity agent behaviors. The main idea

behind the framework is to separate the control task into a pool of independent behaviors, partitioned into so-called *behavior layers*, where each behavior can be defined to inhibit any number of other behaviors from within the same layer. The layers are generally organized in a total order of decreasing abstraction and resolution, and share information via virtual actuators and sensors, controlled by corresponding *actuator and sensor managers*. A parent *behavior manager* links all of the layers together and implements a step routine that controls the execution of the entire structure. The layers are executed in a user-defined order, generally corresponding to the total order from highest level of abstraction to lowest level of abstraction. A key feature of the BC Framework is that multiple behaviors can concurrently be activated in each layer. An overview of the BC Framework architecture is presented in Figure 3.

B. Motivation

As discussed in Section III-B, the Behavior Control Framework was developed as a more powerful and complete solution to the behavior control problem for the NimbRo-OP. Being suitable for use in all application sizes down to the simplest of controllers was no longer a requirement, as it was for the SC Library. Instead, the focus was on the creation of a framework that would facilitate the implementation of complex behavior controllers, suitable for use on the NimbRo-OP and for humanoid soccer. Performance and efficiency of the framework were still of high consideration, as well as its integrability and interoperability with the remaining code. The BC Framework was inspired by, and based on, a custom behavior control architecture that had been in development and use by team NimbRo for almost a decade [24]. Work actually started on the BC Framework as an attempt to extract the architecture of this tried and tested custom implementation into a standalone framework. In the process however, a number of distinct changes were made in order to address the remaining weaknesses of the architecture, while striving to retain its many strengths. Usability, structure and customizability are examples aspects of the architecture to which improvements were made.

C. Behavior Inhibitions

The inhibitions between the behaviors of each behavior layer are processed at the beginning of program execution, before the step routine is first called. At this point, the inhibition definitions are compiled into a directed acyclic graph, referred to as the *inhibition tree*. It is strictly an error if a cycle in the inhibitions exist, as this would lead to unpredictable behavior activations. Individual inhibition definitions can be specified as being either *chaining* or *non-chaining*. The chaining inhibitions are considered to act transitively with other chaining inhibitions, leading to additional implicitly defined inhibitions, while the non-chaining inhibitions do not. Once the inhibition tree has been established, the behaviors are topologically sorted with respect to it, in order to ensure that the resolution of the inhibitions at runtime is unambiguous.

At the beginning of every step, each behavior in a layer is queried for its requested activation level. This is a real number on the unit interval and is a measure of how relevant a behavior is to the current perceived situation. A value of 1.0 corresponds to a request for complete activation, while 0.0 corresponds to complete deactivation. The activation levels are used for
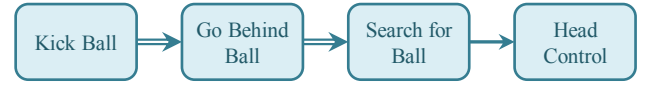

Fig. 4. A simplified example of a ball approach and kick behavior using the BC Framework. Boxes represent behaviors, and the double and single arrows between them represent chaining and non-chaining inhibitions respectively.

two purposes, to evaluate which behavior(s) are active in a layer at any one time, and to aggregate actuator values, as discussed in Section IV-D. The behaviors are traversed in their topological order, and the respective inhibitions are applied multiplicatively. This means for example that if a behavior with an activation level of 0.7 inhibits another behavior of activation level 0.9, then the latter will have its activation level reduced through multiplication by $1 - 0.7 = 0.3$, to 0.27. In by far the most common case, this means that a behavior with an activation level of 1.0 completely prevents all of the behaviors it inhibits from executing. In this way, the requested activation levels are refined into a set of true activation levels.

D. Behavior Layer Data Interfaces

As the hierarchy of behavior layers are executed during a step from the top down, it is generally required that the output of higher order planning in the upper layers is made available to the lower layers. This is done using a network of virtual actuators and sensors. Each layer receives data through its sensors and delivers its output via its actuators. This is a single sender multiple receiver arrangement, where multiple sensors in multiple layers can request to receive the data from the same actuator. Actuators are uniquely identified by name, and support the use of arbitrary data types for information exchange. If the data type numerically supports it, an actuator can be made to be aggregatable. This allows multiple concurrently active behaviors to write to the same actuator. The output that is read by the corresponding sensors is then calculated as the average of the written values, weighted by activation level. This allows competing behaviors to have combined influence on an agent, provided this is desired.

In addition to the transfer of data between layers, there is usually also a need to exchange data with external sources. Most commonly this is in the form of real-world sensory perceptions and motion commands. The concept of interface layers exists for this purpose. From the perspective of the behavior manager, this is simply a normal behavior layer with a slightly modified time of callback execution. This is necessary so that the external data can be sent and received at the appropriate times within a step. In the case of the NimbRo-OP robot, a ROS interface layer was implemented to allow communication of the behaviors node with the other nodes in the system via the inbuilt ROS topics and services. Interface layers also make it possible to split up a behavior control system over process boundaries, meaning that multiple loop rates can be used. For example, higher layers can be made to execute at a slower rate than the more time-critical lower layers.

E. Example

Consider the simple ball approach and kick behavior presented in Figure 4. For simplicity, the system has been

implemented using only a single behavior layer. The blocks represent behaviors, and the double and single arrows between them represent the chaining and non-chaining inhibitions respectively. It should be noted that although no direct arrow exists between *Kick Ball* and *Search for Ball*, the former still inhibits the latter implicitly via the *Go Behind Ball* behavior due to the effect of chaining. Only *Search for Ball* inhibits *Head Control* however, either explicitly or implicitly. In this arrangement each behavior would return a requested activation level of 1.0 if the suitable preconditions are met, and 0.0 otherwise. For example, *Go Behind Ball* would return a 1.0 whenever the sensory perceptions indicate that the ball can be seen on the field, and *Search for Ball* would always return 1.0. Note however that the *Head Control* behavior can still execute whenever the *Search for Ball* behavior is itself inhibited.

A strength of the use of inhibitions is that it leads to a behavioral switching dynamics that is somewhat automated, functioning without the explicit definition of any transitions or the like. For example, consider the *Kick Ball* behavior, which returns an activation level of 1.0 if and only if the ball is directly in front of a foot. Assuming the ball is visible, the robot would walk towards the ball until the preconditions of the kick are met, at which point *Kick Ball* would automatically activate and suppress the *Go Behind Ball* walking behavior. Furthermore, on conclusion of the kick, the walking behavior would automatically reactivate as soon as the kicking behavior reports a zero activation level again. If the ball is suddenly observed once more in an appropriate kicking location, then the walking behavior, or for that matter whichever other behavior is running at the time, once again would temporarily be suppressed while the kick takes over. The advantage of using inhibitions is that all these transitions, which would normally explicitly have to be specified, can be summarized into a very select few inhibition definitions.

V. CONCLUSION

Two frameworks for behavior control have been presented in this paper, the State Controller Library and the Behavior Control Framework. The former is an effective framework for implementing low to mid-level complexity agent behaviors, especially behaviors that have a tendency of requiring structured sequences of actions. It has been demonstrated to be useful in implementing miscellaneous finite state machines required throughout the NimbRo-OP platform code. One limitation of the framework however, is that it does not inherently allow more than one basic behavior to be active at any one time, even if this effect could theoretically be achieved with the use of multithreading. This point, amongst many others, was addressed by the advent of the BC Framework, which utilizes a tree of behavior inhibitions to evaluate at every instant in time which behavior(s) should be activated. This allows multiple aspects of an agent to be controlled simultaneously by independent behaviors. The BC Framework was intended for the implementation of agent behaviors from mid- to high complexity, more so than the SC Library, but it does not preempt the use of the latter. For instance, the SC Library can still be used within the individual behaviors of a BC Framework architecture to implement action sequences based on finite state machines. Both frameworks were designed with performance and efficiency in mind, and form a robust base on which a behavior control system can be built.

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