Flexible Behavior Trees: In search of the mythical HFSMBTH for Collaborative Autonomy in Robotics

Joshua M. Zutell† David C. Conner‡ Philipp Schillinger‡

Abstract—In recent years, the model of computation known as Behavior Trees (BT), first developed in the video game industry, has become more popular in the robotics community for defining discrete behavior switching. BTs are threatening to supplant the venerable Hierarchical Finite State Machine (HFSM) model. In this paper we contrast BT and HFSM, pointing out some potential issues with the BT form, and advocate for a hybrid model of computation that uses both BT and HFSM in ways that leverage their individual strengths. The work introduces a new open-source package for ROS 2 that extends the Flexible Behavior Engine (FlexBE) to enable interaction with BT-based behaviors within a HFSM in a way that supports collaborative autonomy. Simulation and hardware demonstrations illustrate the concepts.

I. INTRODUCTION

This paper advocates for a hybrid model of computation that combines the strengths of the newer Behavior Trees (BT) with the venerable Hierarchical Finite State Machine (HFSM) model. As BTs are the newer model, and have received a great deal of attention in recent years [1]–[8], this paper is partly a defense of HFSM, but only with the aim of encouraging the proper use of both BT and HFSM according to their relative strengths. This paper takes inspiration for its title from a 2017 Game Developers Conference talk by Bobby Anguelov, in which he discusses similar ideas in the realm of video games, and advocates somewhat humorously for “the mythical HFSM BT hybrid (HFSMBTH)” [9].

After comparing the BT and HFSM models, and discussing some potential issues, we introduce our open-source ROS 2 package for enabling a HFSMBT hybrid within the existing open-source Flexible Behavior Engine (FlexBE). The package, dubbed flexible_behavior_trees, allows the user to incorporate the execution and supervision of a BT within a HFSM, while preserving the concept of Collaborative Autonomy that the authors of FlexBE describe in [10], [11]. Fig. 1 shows the results of running a demonstration of the FlexBE-based HFSMBT hybrid.

Section II provides an overview of recent research in applications of BTs to robotics, including a number of open-source BT packages, as well as an overview of a specific HFSM behavior engine called FlexBE [10], [11]. Section III compares BT with simple Finite State Machine (FSM) and Hierarchical FSM, and highlights some potential issues that favor HFSM. Section IV describes a new ROS 2 package that allows a user to incorporate FlexBE state implementations that control execution of a BT in a separate process. Section V presents simulation and hardware demonstrations of robot control using an example HFSMBT hybrid. Section VI summarizes the contributions.

II. RELATED WORK

A. Behavior Trees

Behavior Trees were first developed in the computer gaming industry as a way to increase code reusability, incremental design of functionality, and efficiently test functionality [2], [4]. In particular, BTs are a model of computation used to define control structures for in-game non-player characters (NPC). These NPC are hybrid dynamical systems (HDS), which have both a continuous part like movement and discrete part like decision making; the BT models this by switching between different controllers. As such BTs are a middle layer between high-level AI planning systems and low-level continuous controllers [1].
Moreover, as a general model of computation, BTs offer the benefits of combining the functionalities of sequential behavior compositions, the subsumption architecture, and decision trees to form robust controllers [2], [4]. Having the same capabilities as decision trees, BTs have the potential to be used in machine learning applications [4], [5].

To provide the benefits of these vastly different structures, the main structure of a basic BT is a directed acyclic graph (i.e. a tree) [2], [4]. BTs start at the root node which periodically emits signals called ticks that are sent depth first down the highest priority branch (the leftmost branch by graphical convention). Once a child node receives a tick, it transitions from being idle to executing, and the tick propagates down to its children, until a subsequent node returns either Success, Failure, or Running. Leaf nodes are either Actions or Conditions. Actions may change the world state and may return Success, Failure, or Running; Conditions only report on world state by returning either Success or Failure. These return values are then propagated back up the BT branch to the parent nodes according to specific rules defined by the three basic interior control flow nodes: Fallback, Sequence, and Parallel nodes.

**Fallback nodes**, which are graphically marked as “?” in the BT, are used when there are multiple ways to achieve a goal as illustrated in Fig. 2. Fallback nodes succeed if one of its children succeeds. If the first child of the Fallback node fails (i.e. the "Not Hungry" condition), then the next child will be ticked to execute in sequence until a child returns Success or Running, or all children have returned Failure [2], [4].

For example, in Fig. 2, if hungry, we will first try to eat a sandwich. While this is in process, the **Fallback node returns Running**. On **Successful completion**, the node returns Success. If the “Eat Sandwich” action fails (e.g. no sandwich in refrigerator), then the **Fallback node** will tick the “Eat Apple” action. The **Fallback** will only return Failure if both “Eat Sandwich” and “Eat Apple” fail.

**Sequence nodes**, which are denoted graphically with “→”, are used when actions need to be completed sequentially as displayed in Fig. 3 [2], [4]. Each action is ticked in sequence after the prior action returns Success. A **Sequence node** returns Running or Failure as soon as any child returns Running or Failure. For a **Sequence** to return Success, **all of its children must return Success**.

Lastly, **Parallel nodes**, displayed as “⇒” arrows, are used for executing multiple actions simultaneously [2], [4]. The Parallel node ticks all its children simultaneously. If **M** children out of the total number of children **N** succeed, then the node returns Success. If less than the **M** children succeed, that is more than **N − M** children return Failure, then the **Parallel node returns Failure**.

Table I shows the different node types [2], [4].

| Node        | Success                  | Failure                  | Running                  |
|-------------|--------------------------|--------------------------|--------------------------|
| Action      | Upon completion           | Under to complete         | Staging reaction          |
| Condition   | If True                  | If false                 | Must                      |
| Fallback    | All children return Success | All children return Failure | All children return Failure |
| Sequence    | All children return Success | All children return Failure | All children return Failure |
| Parallel    | M or more children return Success | More than N - M children return Failure | All children return Failure |

**TABLE I**

**SUMMARY OF EACH TYPE OF BT NODE AND RETURN CONDITIONS**

The basic BT design says that on each tick of the root node, the BT traverses the highest priority nodes first. In theory, this allows the BT to be highly reactive, but requires repeated checking of conditions. To avoid large computational burdens of repeated sensor checks, the concept of a “belief vector” that is updated asynchronously is maintained [12].

The common alternative to regular ticking is to use event-driven ticking where a new tick is generated when an action returns Success or Failure, but not when an action is Running, or ticking when an external system triggers an event based on a condition change [13]. This approach reduces reactivity of the BT, and “complexifies” the BT concept, requiring additional tools for monitoring events and analyzing trees. In spite of these drawbacks, event-driven BTs are said to be the most common and de facto standard approach in the video game industry [13].

A powerful concept in designing BTs is the concept of backchaining modular sub-trees from an overall goal [14]. Goal conditions are iteratively expanded with sub-trees that achieve those conditions. This concept applies as both an engineering design approach and algorithm for automated building of a BT. BTs have also been synthesized from Linear Temporal Logic (LTL) specifications [15].

There have been several BT libraries created to implement BTs in C++, Python, and the gaming framework Unity; examples include the **BehaviorTree.CPP**.

https://github.com/BehaviorTree/BehaviorTree.CPP
SpiritTree and NPBehave. The C++ BT framework BehaviorTree.CPP is widely used in robotics, and provides the creation of BTs using XML files with classical nodes and nodes with memory. To create nodes with memory, each XML file defines input and output ports that are accessed by a centralized shared memory called blackboard. Using these ports, the blackboard passes data between different BT nodes where one node’s output data can become another node’s input. In addition to passing data between nodes, there are decorator nodes such as a RepeatNode and RetryNode to execute a node multiple times. The RepeatNode will continue to tick a child node until the child fails. Meanwhile, a RetryNode will continue to tick a child node until the child succeeds. These decorator nodes allow for creating cyclic or partially cyclic behaviors to compensate for an inherently acyclic data structure.

BTs have also made their way into the popular Robot Operating System (ROS), maintained by Open Robotics. The Move Base Flex navigation system uses Behavior Trees instead of HFSMs as a replacement for ROS 1’s navigation package. With the introduction of ROS 2, the navigation package uses behavior trees for task orchestration. It should be noted that both have implicit FSM in their handling of receipt of goals via ROS messages, and transition to execution of the BT.

### B. HFSM and the Flexible Behavior Engine

Prior to the advent of BT, many modern robot systems used Hierarchical Finite State Machines (HFSM) to define a high-level system behavior used to coordinate between subsystems. An early ROS 1 package called SMACH (State MACHINE) allowed users to define such HFSM and execute them on a robot.

In the DARPA Robotics Challenge (2012-15), it was desired for the robot to be a member of a team and not purely autonomous; thus, there was a need for a supervisor to preempt behaviors and reconfigure the robot behaviors in response to changing conditions encountered during a disaster response. As SMACH was not designed for collaborative autonomy, Team ViGIR developed the Flexible Behavior Engine (FlexBE) as a major extension to SMACH. FlexBE supports adjustable autonomy, preemptive state transitions, and online adjustments to behaviors that support collaborative autonomy. FlexBE was released as an open-source ROS package. Fig. 4 shows the four parts of the FlexBE system:

- Onboard (robot) Behavior Executive (OBE)
- OCS User Interface (FlexBE UI)
- OCS HFSM “mirror”
- Various Python-based state implementations

![Fig. 4. FlexBE system architecture (from [20]).](image)

On a robot onboard computer, the Onboard Behavior Executive coordinates execution of the Python-based state implementations and handles coordination of the publish/subscribe to various topics. On a separate computer, FlexBE provides a desktop graphical user interface for the OCS that enables easier development of HFSMs and for monitoring their execution in real-time. The OCS mirror node acts as a bridge between the FlexBE UI and OBE by “mirroring” the status of the onboard state machine without actually executing the states. The mirror communicates with the OBE using standard ROS messaging, and with the FlexBE UI using a JavaScript ROS messaging wrapper. Lastly, the Python-based state implementations encode the HFSM state nodes, and are actions that interact with the robot system processes (e.g., path planning, sensor processing, navigation control). Like SMACH, FlexBE enables the passing of user data from one state to the next. This paper builds upon recent work that has upgraded FlexBE to work with ROS 2.

FSM can be defined using correct-by-construction formal methods techniques, including synthesis of reactive automata from LTL specifications. These techniques have been applied to generating a realized FlexBE-specific HFSM for direct execution of robot control.

In this paper we introduce a new ROS 2 package that enables a user to execute a BT from within a FlexBE HFSM. This realizes the HFSM/BT concept, and enables modular BT sub-trees to be directly incorporated into a reflective HFSM that enables collaborative autonomy.

### III. BT AND HFSM COMPARISON

In this section we discuss the advantages and limitations of both BTs and HFSMs. Following [2], we advocate for a hybrid combination of BT and HFSM that is greater than the sum of their parts. We address three specific claims for benefits of BTs – modularity, two-way data flow, and lack of hidden state – along with their limitation of being acyclic.

While BTs and HFSMs are both equivalent in their computing power, one of the claimed benefits of BTs is their modularity given the weak interdependence between nodes due to the simplified Success, Failure, and Running return values. One can substitute a sub-tree that achieves a pre-condition, or expand an action with a BT that achieves the desired outcome. It is clear however, that this modularity is not absolute and is not free from unintended or emergent impacts on overall system behavior.
Consider the simple examples from Fig. 2 and 3. Using backchaining, the sequence node subtree in Fig. 3 achieves the “Eat Sandwich” action required in Fig. 2. Under normal circumstances, this will satisfy the Failure node and achieve the condition “Not Hungry.” However, consider a case when disposal of the sandwich wrapper fails because the garbage can is full.

In this case, the “Eat Sandwich” action fails, and the Fallback ticks “Eat Apple,” which leads to a case of overeating that was not the desired behavior. One could add a “Blackboard” condition that recognizes the sandwich was already consumed, but this introduces a hidden state into the BT. A good designer might recognize this pitfall, but they do not have control over how the subtrees may be used in the future. It is not always possible to know the best design a priori. One could backchain an action that empties the trash can if it is full before attempting to dispose of the wrapper, but that introduces what could be a relatively low priority task that preempts continuation of an actually higher priority task. We are not arguing that a good BT design cannot overcome this example, only that the modularity is not absolute. Solutions may require ad hoc engineering that violate the basic computational model of the BT, and result in the introduction of hidden control state into the system.

In contrast, a comparable HFSM design would treat the sequence node in Fig. 3 as a simple FSM with multiple labeled outcomes. The overall Success would be the primary outcome, with potential Failure on the separate child actions with unique labels. Making these additional connections is additional work, but the choice becomes explicit. Furthermore, the potential transitions are amenable to formal analysis and correct-by-construction synthesis.

In addition to modularity, BTs are considered favorable over HFSMs due to BTs having two way transitions while HFSMs only have one way transitions. BTs are able to transition up and down the tree using function calls while HFSMs can only transition to the next state sequentially analogous to a Goto statement. Although HFSMs only have one way transitions, HFSMs in both SMACH and FlexBE allow for user data to be defined that is passed along from state to state. While not two-way data flow in the sense that BT have, this concept increases the adaptability of the FSM. As illustrated above, the basic two-way data flow in BTs does not address some conditions without requiring shared data and the introduction of hidden state.

The BT is fundamentally an acyclic directed graph. This has two implications that we highlight here. First, this structure imposes a total order on the resulting behavioral system with an implicit priority that is defined by the preconditions. Functionally, the BT is equivalent to a large collection of ordered if-elif-else blocks. While the priority total ordering is implicit in the structure, it is not readily apparent for larger trees.

The second significant implication is that BTs are often using a fundamentally acyclic data structure to control fundamentally cyclic behaviors. In contrast, defining looping behaviors within an HFSM is natural and readily apparent from the graphical structure of the HFSM. Generating cyclical behaviors using a BT paradigm is clearly possible, but does so via external triggers and decorators; the cyclical behavior is not obvious from the graphical structure of the BT.

Finally, the FlexBE system supports collaborative autonomy. HFSM are a natural representation for humans to follow, and the transitions readily encode the expected transitions and contingency plans in the form of a script. FlexBE HFSM support adjustable autonomy and operator interactions via preemption and blocked transitions.

The remainder of this paper describes a system for incorporating BT subtrees into a FlexBE HFSM to support cyclic behaviors and the best use of BTs according to their relative strengths. The work enables the “mythical HFSMBT hybrid” that builds upon the strengths of both BT and HFSM to achieve something greater than either alone.

IV. FLEXIBLE BEHAVIOR TREES

To combine the benefits of HFSMs and BTs, we developed the flexible_behavior_trees ROS package to enable embedding BTs into FlexBE HFSMs. The package contains a BT server node derived from the ROS 2 navigation2 nav2_behavior_tree package, which is based on the BehaviorTree.CPP framework. Following the ROS 2 navigation2 BT server format, the BTs are encoded as XML files, which are parsed and loaded into the BT server where they are stored by behavior name. The flexible_behavior_trees package defines custom ROS Actions – BtLoad and BtExecute – and corresponding FlexBE state implementations BtLoadState, BtExecuteState, and BtExecuteGoalState.

FlexBE initiates BT execution by sending a BtExecute action goal to the BT server node with a designated behavior name to execute. To monitor progress of executing a BT, the BT server sends BtExecute action feedback messages containing which BT nodes are active, current location of the robot, and how long the BT has been executing. Once a BT has finished executing, the BT server will respond to the BtExecute result message that indicated whether the BT returned Success, Failure, or if execution was canceled due to a BtExecute cancel message.

The flexible_behavior_trees package also defines three states: BtLoaderState, BtExecuteState, and BtExecuteGoalState that interface with the BT server node. The BtLoaderState creates and sends a custom BtLoad goal message containing a list of BT XML files for the BT server to load. The motivation for this BtLoaderState is to allow a user to load relevant BTs prior to execution. Next, the BtExecuteState sends a goal message to the BT server to execute a specified BT by name. The BtExecuteGoalState works similarly, but adds either one or multiple PoseStamped message to the BtExecute goal for basic navigation behaviors and

https://github.com/FlexBE/flexible_behavior_trees
other behaviors requiring user defined goals. After sending the goal to the BT server and receiving the result back from the BT server, the FlexBE BT state implementations return transitions labeled done, failed, or canceled corresponding to the BT results.

Using FlexBE and flexible_behavior_trees states, larger BTs can be deconstructed into smaller sub-trees, while using FlexBe’s collaborative autonomy benefits by adding more FlexBE states to the HFSM. This allows more user intervention while preserving the modularity benefits of BTs. These sub-trees on the BT server are able to share data through BehaviorTree.CPP’s blackboard.

V. DEMONSTRATION

In this section we will discuss two demonstrations of the Flexible Behavior Trees. The first demonstration loaded a BT similar to the ROS 2 navigation2 BT in Fig. 5 and executed from a FlexBE HFSM shown in Fig. 6 this makes the FSM that is implicit in the navigation2 explicit to support collaborative autonomy. Meanwhile, the second demonstration split the BT from Fig. 5 into separate sub-trees – global planner, controller, and recovery behaviors – interfaced by separate FlexBE state implementations shown in Fig. 7. The complete setup for both the simulation and hardware demonstrations are provided.

In the first demonstration, the HFSMBTH behavior in Fig. 5 gets a goal from the user and sends it to the BT server to navigate independently to the goal. This is similar to operation of the ROS 2 Navigation2 Stack with additional collaborative autonomy that allows the user to cancel and re-enter another goal if they do not like the selected target. After navigating to the goal, the HFSMBTH loops to ask the user for another goal. The HFSMBTH returns failed if the BT result returns failure.

The second demonstrated HFSMBTH behavior, as shown in Fig. 1, splits the first demonstration BT into sub-trees providing for more user intervention. The behavior first loads all the BTs that will be executed and then asks the user for a target goal. After receiving this goal, the HFSMBTH behavior transitions into creating a global plan to the goal. Using the adjustable autonomy feature of FlexBE, the user can first view the returned path (using RViz in this example), and either accept the plan as is by allowing the HFSM transition, or choose the canceled outcome to require input of another target goal as illustrated in Fig. 7. Upon accepting the plan, the HFSMBTH transitions into navigating towards the goal using a controller. The BT action controller is able to receive the plan from the global planner through the BehaviorTree.CPP’s blackboard. During navigation, the user is able to monitor the execution and preempt the navigation state via the FlexBE UI. Moreover, both the global planner and navigation states allow the user to manually stop execution or force transition into performing recovery behaviors in case of an emergency. The recovery behaviors state will perform the specified recovery actions in the BT, and upon successful completion transitions to ask the user for another goal. In this simple example, if the recovery behaviors return Failure, the state return failed transition and the HFSMBTH ends navigation.

These HFSMBTH behaviors were tested in Gazebo-based simulation using a TurtleBot3 model, and on hardware with a TurtleBot2 as shown in Fig. 1. The software runs under Ubuntu 20.04 using the ROS 2 “Foxy Fitzroy” distribution. The demonstrations use the ROS 2 versions of FlexBE, Gazebo, RViz2, and navigation2 software, in addition to standard sensor drivers. Complete directions are provided.

VI. CONCLUSIONS

This paper advocates for a hybrid model of computation that combines the strengths of the newer Behavior Trees (BT) with the venerable Hierarchical Finite State Machine (HFSM) model. After discussing the relative strengths and weaknesses of BT and HFSM, we introduce a new open-source ROS 2 package flexible_behavior_trees that enables a user to provide supervisory control of a behavior tree from within a FlexBE state machine. This
enables collaborative autonomy, while leveraging the relative strengths of both BT and HFSM as the appropriate level of abstraction. Simulation and hardware demonstrations are presented and released open-source.

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