Behavior Trees as a Representation for Medical Procedures

Blake Hannaford
Biorobotics Laboratory
Department of Electrical Engineering
The University of Washington
January 25, 2018

Abstract Behavior trees (BTs) emerged from video game development as a graphical language for modeling intelligent agent behavior. BTs have several properties which are attractive for modeling medical procedures including human-readability, authoring tools, and composability. This paper will illustrate construction of BTs for exemplary medical procedures.

1 Introduction

Prior to about 2010, the term Behavior Tree (BT) was used idiosyncratically by several authors, but around that time a literature began to emerge around a tree model of behaviors used by the game industry for AI-based characters[1, 2]. These BTs assume that units of intelligent behavior (such as sensing procedures or sense/action pairs) can be programmed such that they perform a piece of an overall task/behavior, and that they can determine and return a 1-bit result indicating success or failure. These units are the leaves of BTs. The level of abstraction of BT leaves is not specified by the BT formalism and varies from one application to another. In the context of medical robotics, they could be things such as a guarded move, a precision cutting action, acquisition of an ultrasound image, creation of a plan, etc. Earlier medical robotics systems such as Robodoc addressed the problem with, for example, scripting languages[3]. Recent literature has applied BTs to UAV control[4], humanoid robotic control[5], and human-robot cooperation in manufacturing[6]. Theoretical classification of BTs has been studied by several authors[7] which has formally related BTs to Finite State Machines (FSMs). BTs have advantages of modularity and scalability with respect to finite state machines. Other theoretical studies have related BTs to Hybrid Dynamical Systems[8], humanoid robotic behavior[5], and derivation of correctness guarantees[9]. Software packages and ROS implementations are now available[10]. Several of the above references have ample introductory material and examples of BT concepts.

When implementing intelligent behavior with BTs, the designer of a robotic control system breaks the task down into modules (BT leaves) which return either “success” or “failure” when called by parent nodes. All higher level nodes define composition rules to combine the leaves including: Sequence, Selector, and Parallel node types. A Sequence node defines the order of execution of leaves and returns success if all leaves succeed in order. A Selector node (also called “Priority” node by some authors) tries leaf behaviors in a fixed order, returning success when a node succeeds, and failure if all leaves fail. Decorator nodes have a single child and can modify behavior of their children with rules such as “repeat until X > 0”. BTs have been explored in the context of humanoid robot control[10][11][12] and as a modeling language for intelligent robotic surgical procedures[13].

In this paper, we explore the use of BTs to represent medical procedures (often referred to as algorithms). We will illustrate this use by converting published algorithms given in the literature to BTs.

---

1 We are pleased to acknowledge support from National Science Foundation grant #IIS-1637444 and collaborations on that project with Johns Hopkins University and Worcester Polytechnic Institute.

2 https://github.com/miccol/ROS-Behavior-Tree
2 Example 1. Blood Draw

The World Health Organization issues a best practices document on drawing blood for medical tests (phlebotomy). This over-100-page document gives many details for each step of what is mostly a serial process with few branches. A BT representing the first several steps of this process was developed and is represented in Figure 1.

The root (top) node, Φ, encapsulates task start, task end, and task “succeed/fail” status. Its only child (BT root always has just one child) is a Sequence node (→) indicating that execution will be passed to each child in sequence from left to right as shown, with “Failure” returned by the node if any child returns “Failure”. The first child is also a sequence node which secures equipment and paperwork, and assesses the overall readiness of the patient. In this and subsequent diagrams, we use Yellow to indicate a query or sensing operation which returns “Success” or “Failure” based only on sensing of the world state (in this case if the patient is ready). Green leafs indicate tasks that are physically performed. The second child of the main “Sequence” node is a “Selector” node in which the phlebotomist determines whether or not a suitable vein is present in the left or right arm. If neither arm shows a suitable vein then the “Selector” node will fail and that failure will propagate up to the Sequence and in turn to the tree itself.

Figure 1: BT constructed for the emergency airway procedure of 14.
3 Example 2. Emergency Airway Ventilation

Figure 2: Existing representations of airway establishment include Left: American Society of Anesthesiology [16], Right: Davis et al. [17]

Human life will expire in minutes if the upper airway is blocked. A medical team thus must quickly follow a best practice sequence of interventions until airflow is reestablished. Restoration of airway consists of a rapid succession of increasingly invasive steps, starting with insertion of a laryngoscope, and, as a last resort, surgical opening of the airway through cricothyroidotomy. The literature on airway restoration algorithms contains many diagrammatic languages for representation of the airway algorithm. One such diagram includes an exception in the form of a box to the side of a flowchart containing:

“If SpO2 drops to 93% at any point: Facemask + OPA or SGA. If no ETCO2 with best attempts, progress to surgical airway.” [14]

This box can is explicitly outside the flowchart but indicates a concurrent monitoring and interrupt task which is hard to represent in the original selected notation.

Figure 3: BT constructed for the emergency airway procedure of [14].

We constructed a BT for the airway procedure (Figure 3) based on [14] and interpreted by https://emcrit.org/racc/shock-trauma-center-failed-airway-algorithm/. The first logic node (directly below Φ) is a “parallel” node, which indicates that its children should execute concurrently. The left-most child of the parallel node represents the concurrent monitoring procedure represented as a side box in [14]. The
right branch, defining the main algorithm, contains a sequence node ($\rightarrow$). Its left-most child in turn is a “Selector” node which allows for alternative methods, returning when the first of its children succeeds. It can be verified that in the procedure depicted by this BT, the surgical airway procedure (as seen in the movies) is a last-resort which only is attempted when laryngoscopy (up to 3 attempts) and Intubating SGA placement (two attempts) fail.

Compared to the flowchart of [14], the BT is a uniform representation which clearly labels alternative strategies and fallbacks (via the “?” (Selector) nodes), and is amenable to direct software execution (assuming code modules (such as for example ROS nodes) are available for each leaf.)
Figure 4: BT constructed detection and ablation/treatment of positive tumor margins [13]. A blackboard data store is commonly used with BTs to allow them to share information.

4 Example 3. Simulated Tumor Margin Ablation

In recent bench-top surgical robotics experiments [13, 18] a system was developed which illustrated a future surgical scenario for treatment of glioma. In this scenario, a surgeon will expose the tumor and manually remove it, but the problem remains of detecting and treating any remaining tumor material at the edge of the resulting cavity. In many cancer surgeries, a margin of up to a centimeter is taken around the tumor to increase the odds that no residual cells are left behind.

In this work, Hu et al. assumed the existence of a currently-under-development biomarker for brain tumors [19] which would allow residual tumor material to be detected through fluorescence. They developed a robotic system which could scan the cavity for simulated fluorescence, detect a response, and plan and execute one or more treatment plans.

The BT we developed (Figure 4) performs this task, and checks up to four planning algorithms (lower left leaves) for appropriateness depending on the area and shape of the detected fluorescent region. Notably Hu et al., developed a new type of node, the “Recovery” node, which is able to fall back to a recovery tree in the event of a task failure.

Another notable feature of this Medical BT is the “Select” leaf. In this implementation, selecting of the plan from among several computed plans, was performed by manual input from a surgeon. Thus the BT framework can easily incorporate manual steps into a complex and composable procedure. Furthermore, should an automated function be developed with sufficient confidence, it can easily be dropped in to the select leaf node of the BT.
5 Conclusion

The use of BTs for medical algorithms is still conceptual. Anticipated uses to be developed and validated in the future include

- Documentation of “standard of care” algorithms for human medical providers.
- Execution frameworks for automated medical robotic tasks
- Description and coordination of Human-Robot-Collaborative Systems\[20, 6\] in medical robotics.

Compared to Finite State Machines, Hidden Markov Models, and similar approaches, BTs afford a human-readable and writable representation through its small number of relatively easy to understand combinatorial operators: “Sequence” and “Selector”, and the ease by which BTs can be combined (using those same operators). These properties seem to be well matched to conventional human thinking about procedures.

There are also limitations of BTs which need further exploration and elucidation to make sure they are used appropriately. For example

- BTs do not have an explicit “interrupt” mechanism by which an ongoing procedure can be stopped.
- New safety checking mechanisms (such as the “Recovery” node described in Hu et. al.\[13, 18\]) need further development and unification.
- Learning of BTs is still very much an open problem. Initial study\[2\] and more recent works\[21, 22\] suggest some possibilities for on-line autonomous performance improvement.
References

[1] Damián Isla. Building a better battle: The halo 3 ai objectives system. http://web.cs.wpi.edu/~rich/courses/imgd4000-d09/lectures/halo3.pdf

[2] Chong-U Lim, Robin Baumgarten, and Simon Colton. Evolving behaviour trees for the commercial game defcon. In European Conference on the Applications of Evolutionary Computation, pages 100–110. Springer, 2010.

[3] P Kazanzides, J Zuhars, B Mittelstadt, B Williamson, P Cain, F Smith, L Rose, and B Musits. Architecture of a surgical robot. In Systems, Man and Cybernetics, 1992., IEEE International Conference on, pages 1624–1629. IEEE, 1992.

[4] Petter Ogren. Increasing modularity of uav control systems using computer game behavior trees. In AIAA Guidance, Navigation and Control Conference, Minneapolis, MN, 2012.

[5] Jana Tumova, Alejandro Marzinotto, Dimos V Dimarogonas, and Danica Kragic. Maximally satisfying ltl action planning. In Intelligent Robots and Systems (IROS 2014), 2014 IEEE/RSJ International Conference on, pages 1503–1510. IEEE, 2014.

[6] Chris Paxton, Andrew Hundt, Felix Jonathan, Kelleher Guerin, and Gregory D Hager. Costar: Instructing collaborative robots with behavior trees and vision. In Robotics and Automation (ICRA), 2017 IEEE International Conference on, pages 564–571. IEEE, 2017.

[7] M. Colledanchise and P. gren. How Behavior Trees Modularize Hybrid Control Systems and Generalize Sequential Behavior Compositions, the Subsumption Architecture, and Decision Trees. IEEE Transactions on Robotics, 33(2):372–389, April 2017.

[8] Michele Colledanchise and Petter ¨Ogren. How behavior trees modularize robustness and safety in hybrid systems. In Intelligent Robots and Systems (IROS 2014), 2014 IEEE/RSJ International Conference on, pages 1482–1488. IEEE, 2014.

[9] Michele Colledanchise, Richard M Murray, and Petter ¨Ogren. Synthesis of correct-by-construction behavior trees. In Intelligent Robots and Systems (IROS 2017), 2014 IEEE/RSJ International Conference on. IEEE, 2017.

[10] Alejandro Marzinotto, Michele Colledanchise, Christian Smith, and Petter ¨Ogren. Towards a unified behavior trees framework for robot control. In 2014 IEEE International Conference on Robotics and Automation (ICRA), pages 5420–5427. IEEE, 2014.

[11] Michele Colledanchise, Alejandro Marzinotto, and Petter ¨Ogren. Performance analysis of stochastic behavior trees. In 2014 IEEE International Conference on Robotics and Automation (ICRA), pages 3265–3272. IEEE, 2014.

[12] J Andrew Bagnell, Felipe Cavalcanti, Lei Cui, Thomas Galluzzo, Martial Hebert, Moslem Kazemi, Matthew Klingensmith, Jacqueline Libby, Tian Yu Liu, Nancy Pollard, et al. An integrated system for autonomous robotics manipulation. In 2012 IEEE/RSJ International Conference on Intelligent Robots and Systems, pages 2955–2962. IEEE, 2012.

[13] Danying Hu, Yuanzheng Gong, Blake Hannaford, and Eric J Seibel. Semi-autonomous simulated brain tumor ablation with ravenii surgical robot using behavior tree. In 2015 IEEE International Conference on Robotics and Automation (ICRA), pages 3868–3875. IEEE, 2015.

[14] Christopher T Stephens, Stephanie Kahntroff, and Richard P Dutton. The success of emergency endotracheal intubation in trauma patients: a 10-year experience at a major adult trauma referral center. Anesthesia & Analgesia, 109(3):866–872, 2009.

[15] World Health Organization et al. WHO guidelines on drawing blood: best practices in phlebotomy. Geneva: World Health Organization, 2010.

[16] William H Rosenblatt. The airway approach algorithm: a decision tree for organizing preoperative airway information. Journal of clinical anesthesia, 16(4):312–316, 2004.
[17] Daniel P Davis, Colleen Buono, Janie Ford, Lorien Paulson, William Koenig, and Dale Carrison. The effectiveness of a novel, algorithm-based difficult airway curriculum for air medical crews using human patient simulators. *Prehospital Emergency Care*, 11(1):72–79, 2007.

[18] Danying Hu, Yuanzheng Gong, Eric J Seibel, Laligam N Sekhar, and Blake Hannaford. Semi-autonomous image-guided brain tumour resection using an integrated robotic system: A bench-top study. *The International Journal of Medical Robotics and Computer Assisted Surgery*, 2017.

[19] Mandana Veiseh, Patrik Gabikian, S-Bahram Bahrami, Omid Veiseh, Miqin Zhang, Robert C Hackman, Ali C Ravanpay, Mark R Stroud, Yumiko Kusuma, Stacey J Hansen, et al. Tumor paint: a chlorotoxin: Cy5. 5 bioconjugate for intraoperative visualization of cancer foci. *Cancer research*, 67(14):6882–6888, 2007.

[20] Danica Kragic, Panadda Marayong, Ming Li, Allison M Okamura, and Gregory D Hager. Human-machine collaborative systems for microsurgical applications. *The International Journal of Robotics Research*, 24(9):731–741, 2005.

[21] Michele Colledanchise, Ramvivas Parasuraman, and Petter Ögren. Learning of behavior trees for autonomous agents. *arXiv preprint arXiv:1504.05811*, 2015.

[22] Blake Hannaford, Danying Hu, Dianmu Zhang, and Yangming Li. Simulation results on selector adaptation in behavior trees. *ArXiv*, abs/1606.09219, 2016.