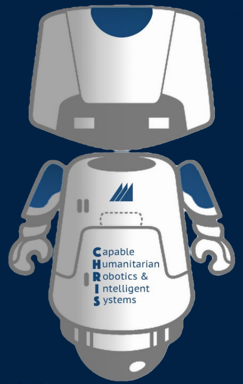
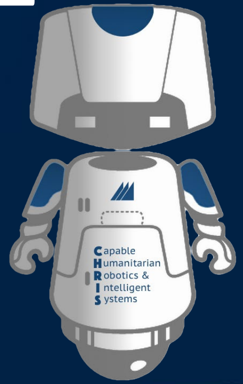
Christopher Newport University
Department of Physics, Computer Science & Engineering

FlexBE -The Flexible Behavior Engine: Collaborative Autonomy for ROS 2

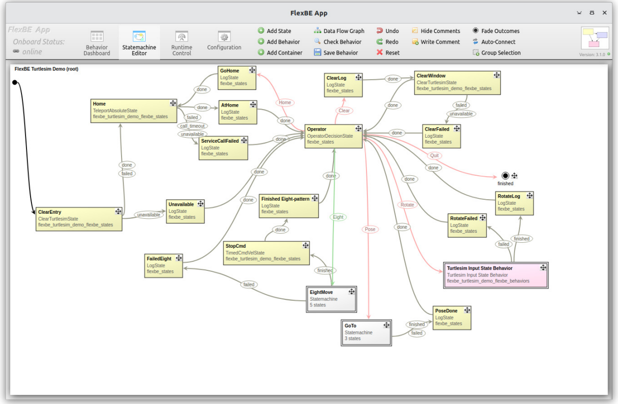


David C. Conner, PhD
Associate Professor
robotics@cnu.edu

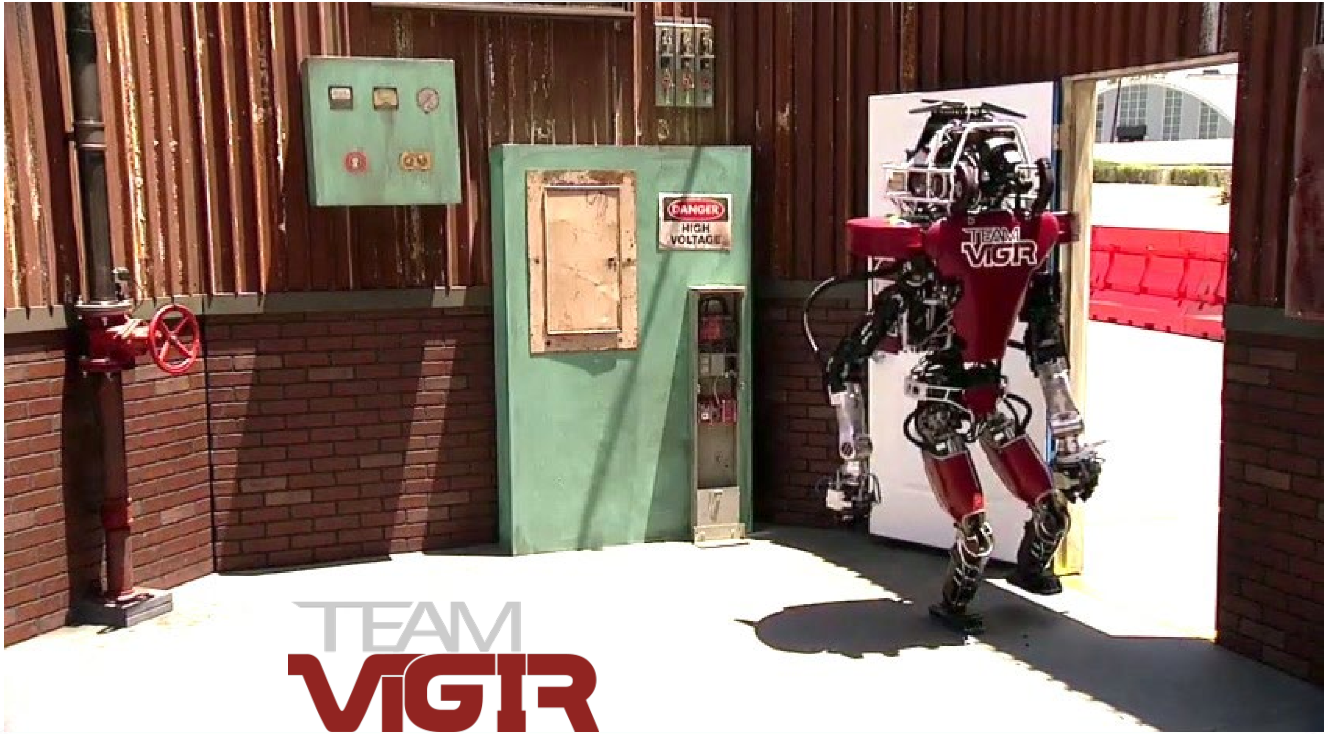


FlexBE Overview

- History and background
- Key features and design
- Related ROS packages
- Ongoing research and development



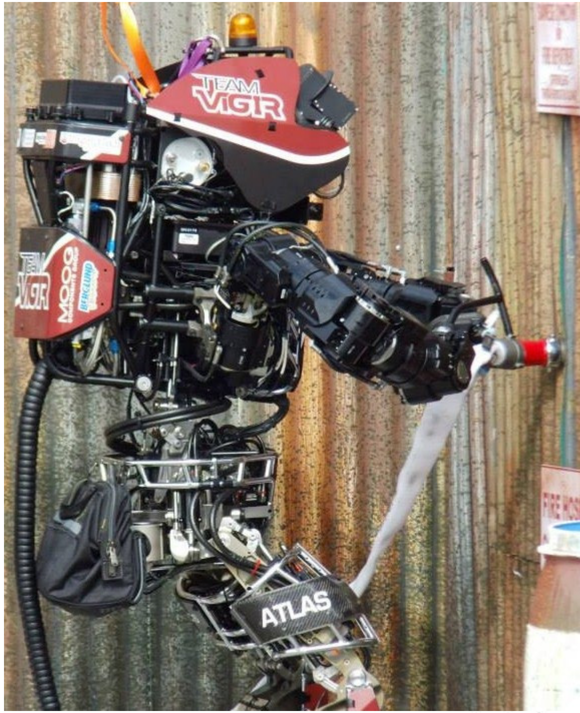
Team ViGIR's Atlas at the 2015 DARPA Robotics Challenge Finals



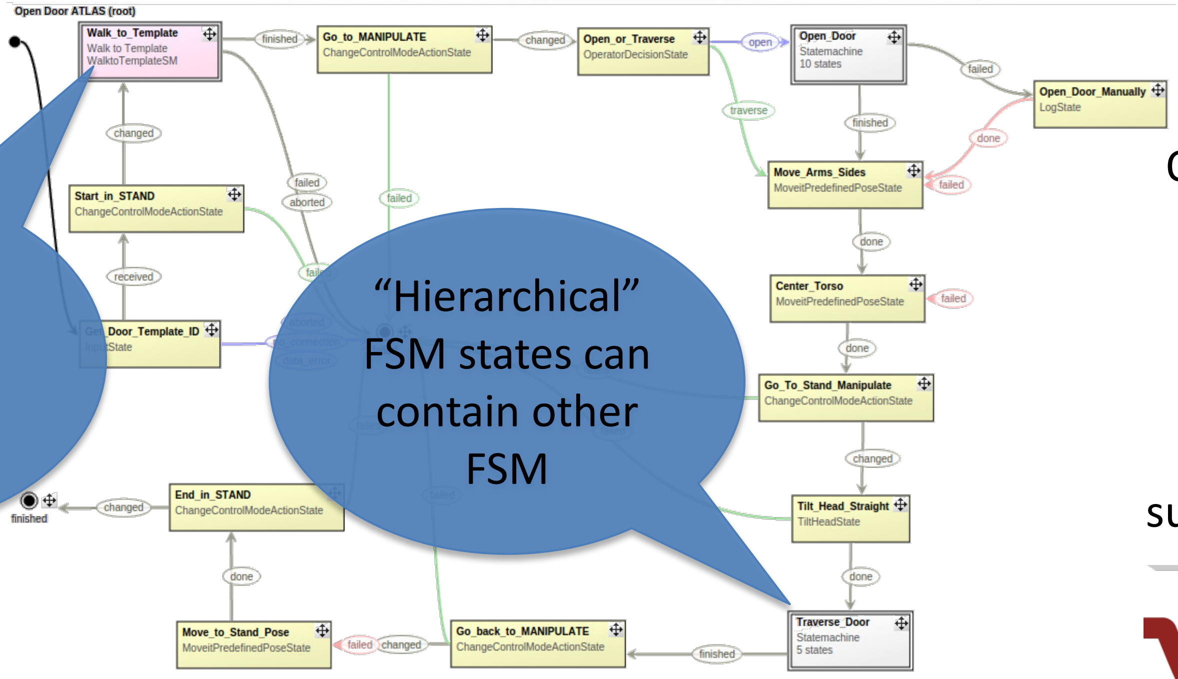
DARPA Robotics Challenge (DRC)

- Human-robot teams
- Supervised autonomy
  - Operators can inject information
  - Operators can preempt behaviors
- Constrained communications

TEAM VIGIR



Hierarchical Finite State Machines



Compose behaviors within behaviors

"Hierarchical" FSM states can contain other FSM

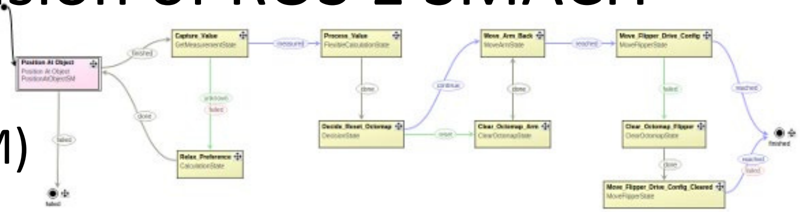
2015 DRC
Open Door Task
High-level
Behavior

HFSM acts as a script for supervisors/robot

TEAM VIGIR

FlexBE : The Flexible Behavior Engine

- Originally conceived as an extension of ROS 1 SMACH
  - http://wiki.ros.org/smach
  - Hierarchical Finite State Machines (HFSM)
  - Python-based state implementations



- Initially developed by Philipp Schillinger

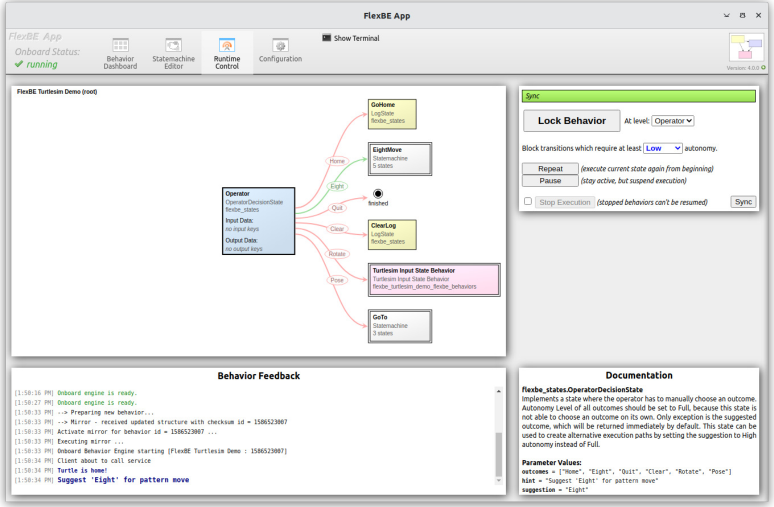
  @ TU Darmstadt (Germany)

- ROS 1 open-source release in Fall 2015
  - http://wiki.ros.org/flexbe
  - http://github.com/FlexBE

http://philserver.bplaced.net/fbe/applications.php

Key Design Concepts

- Support for high-level behavior control
  - Hierarchical Finite State Machines
  - Natural interaction with system capabilities
  - Concurrent state execution
  - Adjustable/sliding autonomy levels
    - Support for unsupervised fully autonomous mode
  - Runtime modifiable behaviors
- Intuitive GUI
  - State machine (behavior) editor
  - Interactive operator/supervisor runtime interface
    - Enable "Collaborative Autonomy"



https://onlinelibrary.wiley.com/doi/full/10.1002/rob.21671

Continuing Development @ CNU

- Christopher Newport University

  Dept. of Physics, Computer Science and Engineering

  - FlexBE used in “Introduction to Robotics”

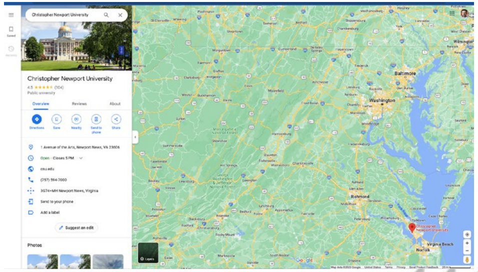
- Recent releases

  In collaboration with Philipp Schillinger

  - Final ROS 1 Noetic release May 2023
  - ROS 2 Conversion
    - Initial source released summer of ’22
    - Humble and Iron binaries summer ‘23

https://cnu.edu

4500 students in SE VA



Key Features and Design

Key Features and Design

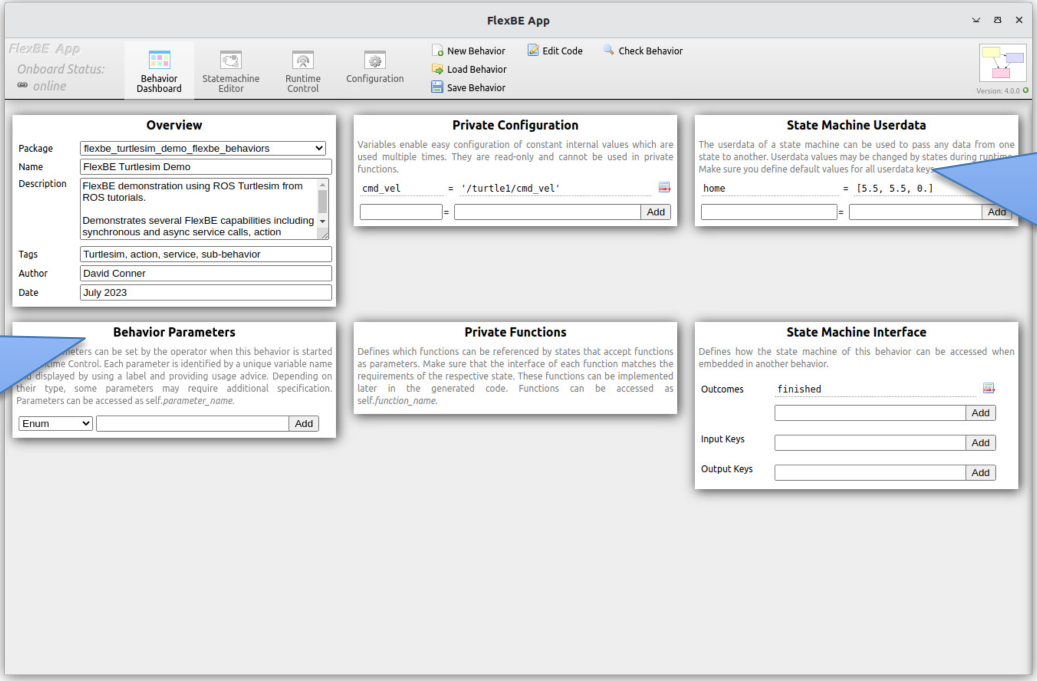
FlexBE is

- Python-based
  - Easy state implementation development
- NOT for high-rate control
  - Desired update rate in tens of Hz
- NOT for real-time control
- NOT for verifiable safety critical systems

FlexBE can easily interact with such systems

The purpose of FlexBE is high-level behavioral control systems.

FlexBE GUI : Behavior Dashboard

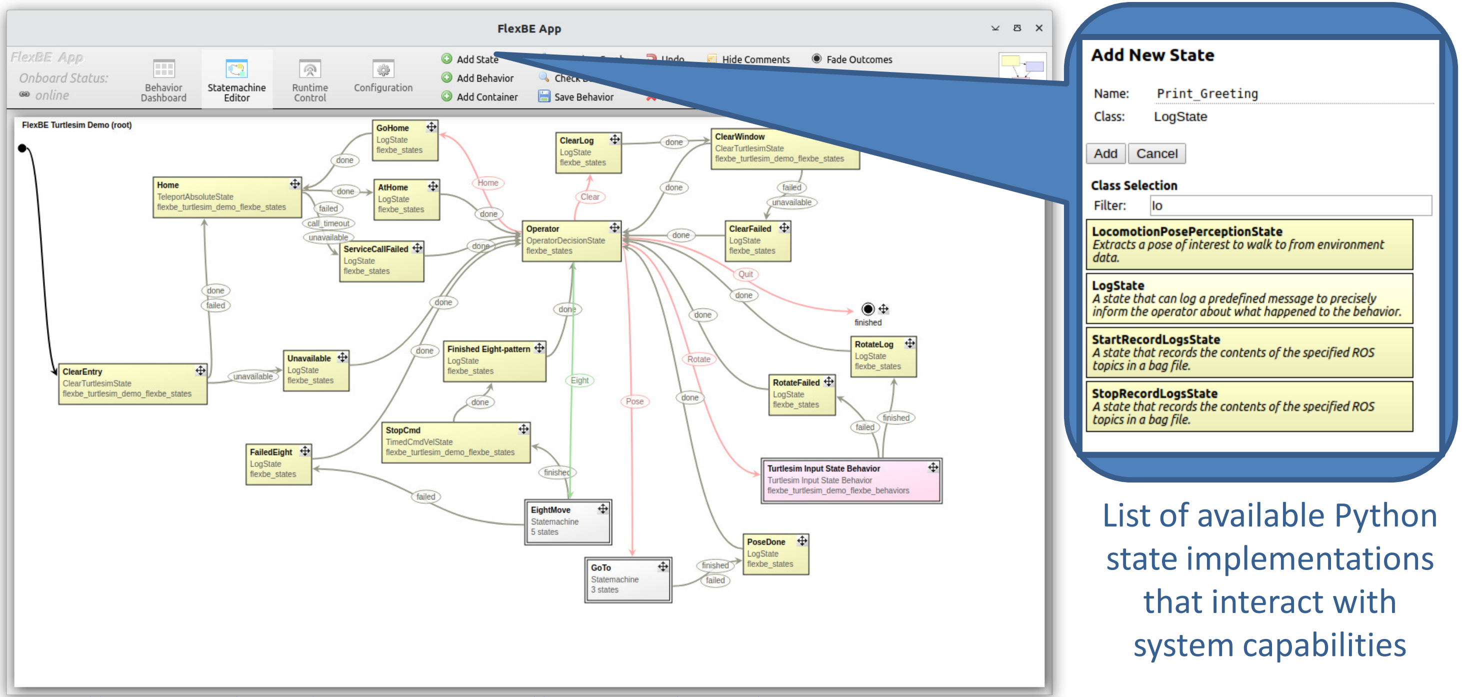


FlexBE allows parameters to be configured at runtime

FlexBE allows modifiable "userdata" to be passed from state to state

http://wiki.ros.org/flexbe/Tutorials and https://github.com/FlexBE/flexbe_turtlesim_demo

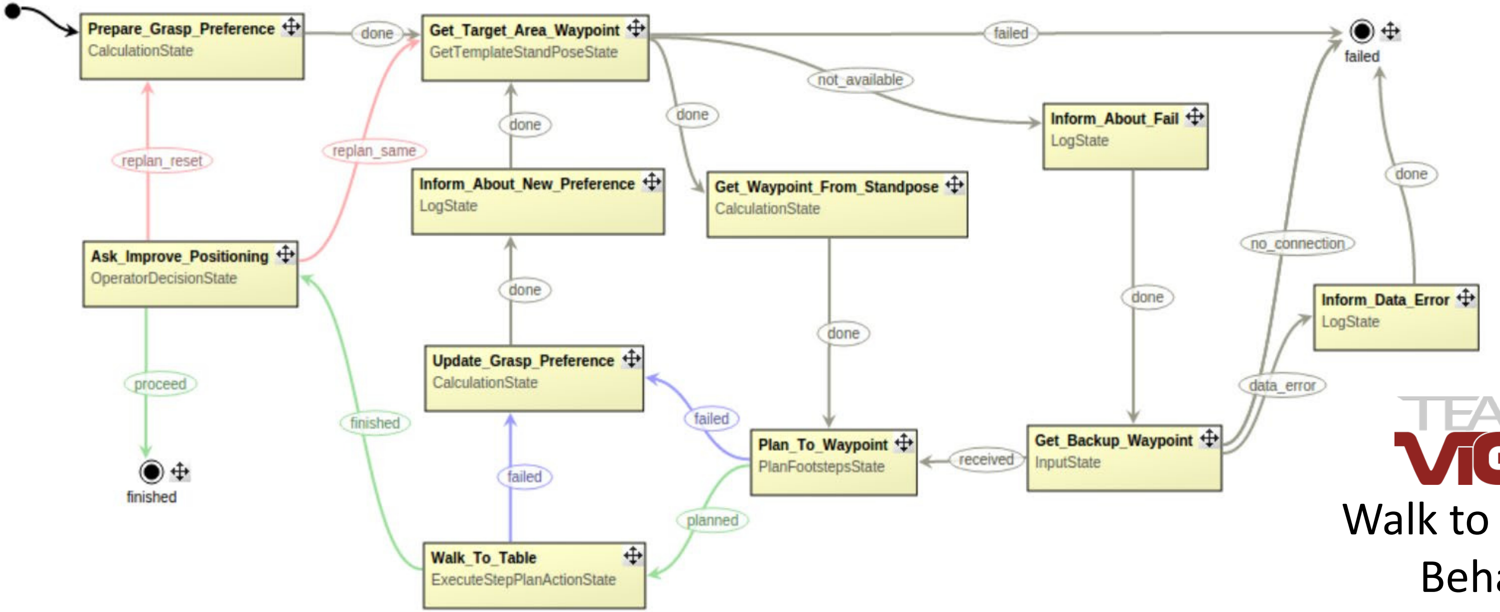
FlexBE GUI : Statemachine Editor



List of available Python state implementations that interact with system capabilities

http://wiki.ros.org/flexbe/Tutorials and https://github.com/FlexBE/flexbe_turtlesim_demo

FlexBE Behavior Example

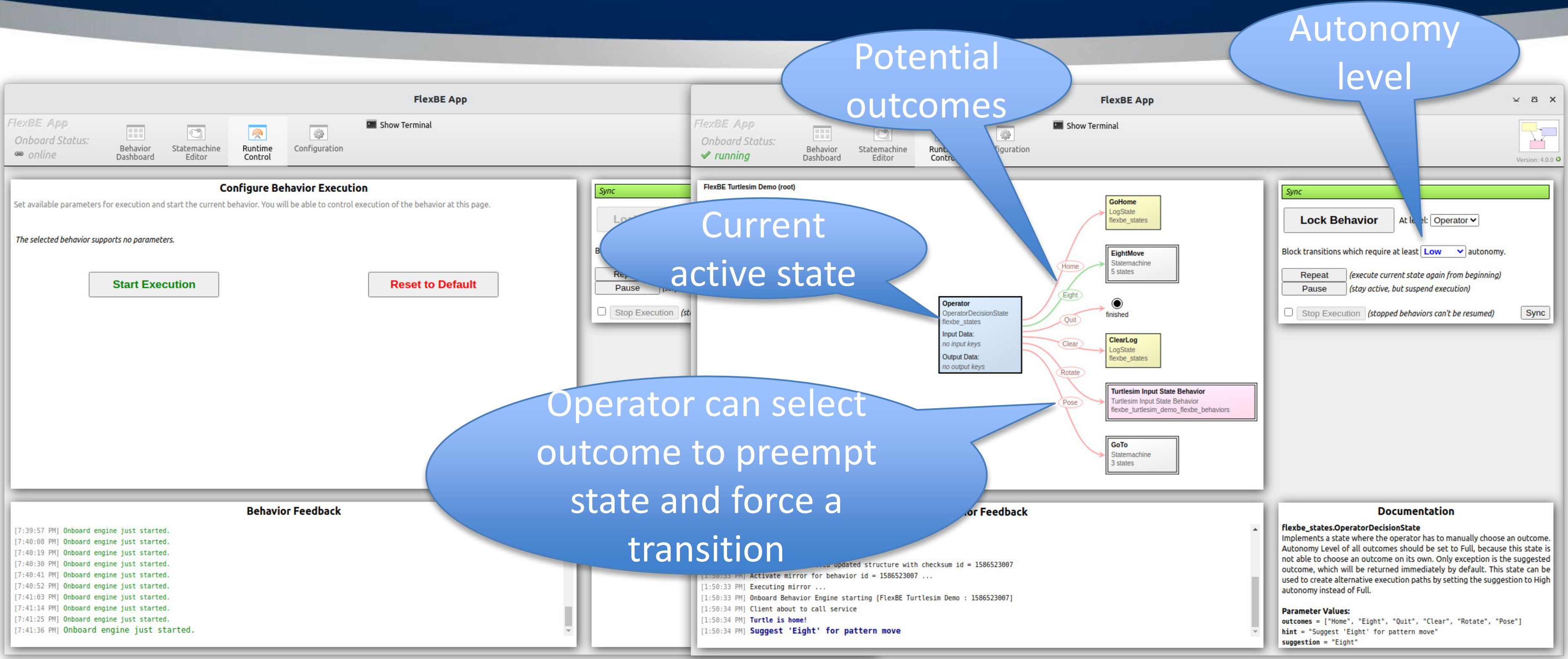


TEAM VIGIR

Walk to Template Behavior

A state machine realizes a desired "behavior" by invoking system capabilities; behavior state machines can be composed.

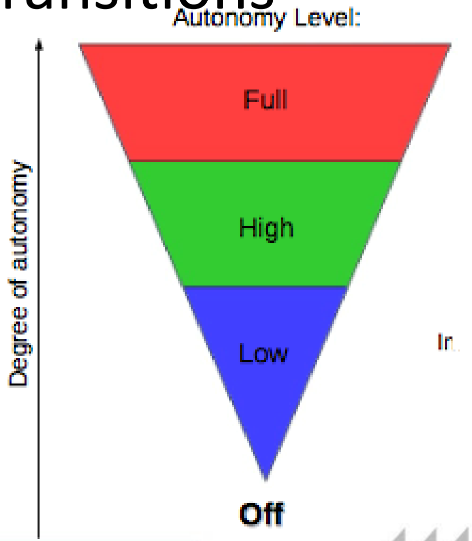
FlexBE GUI : Runtime Control



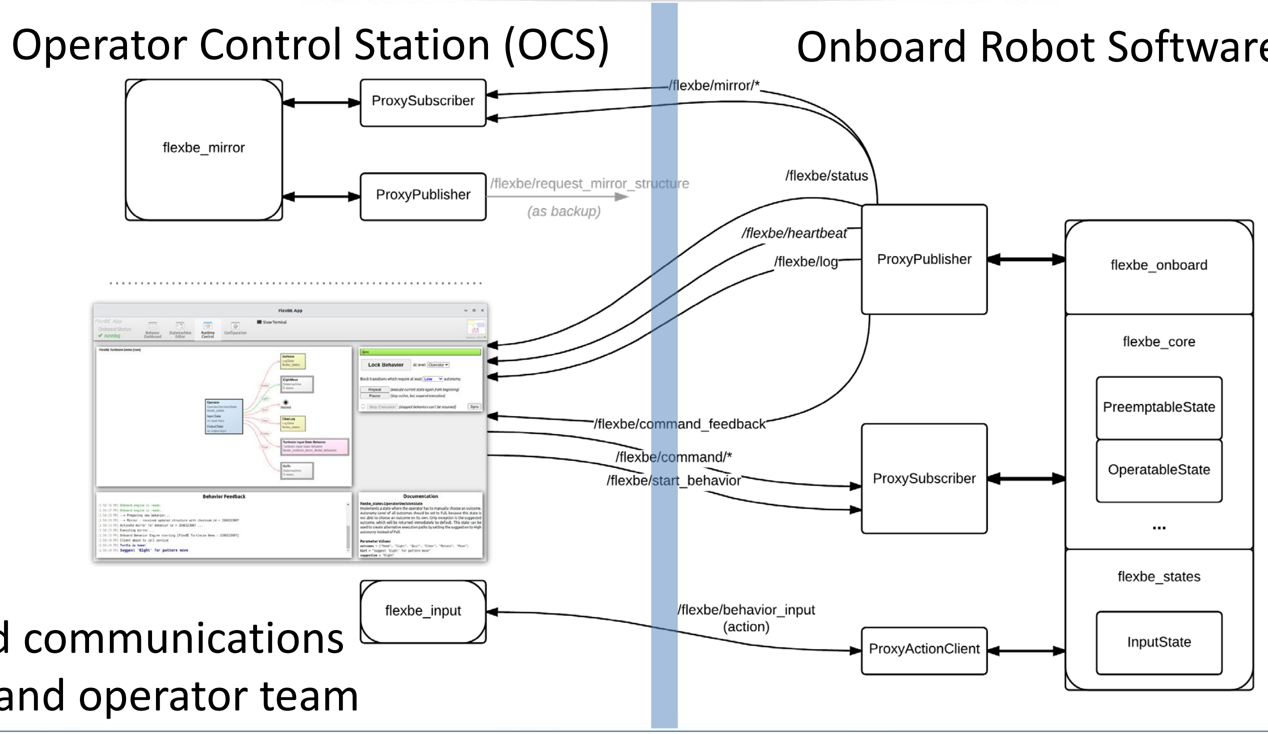
http://wiki.ros.org/flexbe/Tutorials and https://github.com/FlexBE/flexbe_turtlesim_demo

Key Design Concepts

- Sliding autonomy levels
  - Low requires operator to confirm some transitions
    - i.e., it blocks exit transition
  - Full allows fully autonomous transitions
- Lockable states and edit on the fly
- Enable operator forced transitions



FlexBE Communications



States share pub/sub/action interfaces via "proxies"

DRC constrained communications between robot and operator team

FlexBE States and ROS 2 Actions

- States interact with system capabilities
- Commonly implement an action client interface
  - Send goal **`on_enter`**
  - Monitor feedback and result in **`execute`**
  - Return outcome and **`on_exit`** transition on action **`result`**

For example, see code for topic-, service-, and action-based state implementations at
https://github.com/FlexBE/flexbe_turtlesim_demo/tree/ros2-devel/flexbe_turtlesim_demo_flexbe_states/flexbe_turtlesim_demo_flexbe_states

Significant Upgrades @ CNU

- ROS 2 conversion
  - Initial source released summer of ’22
  - Refinements and cleanup in summer ‘23
  - Humble and Iron binaries summer ’23
  - Enhancements to concurrent states in ros2-pre-release branch
    - Planned release to Iron coming soon

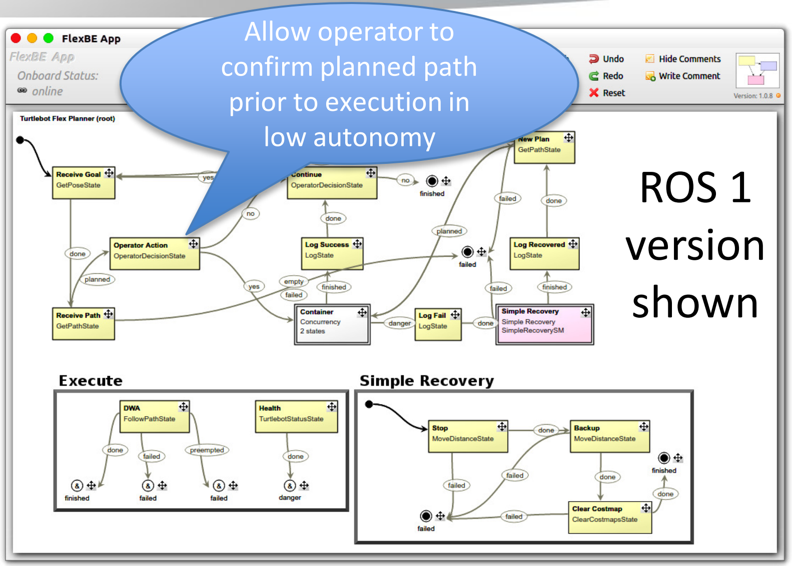
Summer ’23 work supported under Naval Engineering Education Consortium (NEEC) grant N00174-23-1-0018

Related ROS Packages

Related ROS Packages

Flexible Navigation Package

- Collaborative navigation
  - Allow approval of plans or replan
  - Separate global and local planners
- FlexBE state implementations interface to Nav2 capabilities
  - State implementations
  - Special Nav2 compatible nodes



https://github.com/FlexBE/flexible_navigation
https://ieeexplore.ieee.org/document/7925266
https://ieeexplore.ieee.org/document/9764047
https://github.com/FlexBE/flex_nav_turtlebot3_demo

Flexible Behavior Trees

- Behavior trees are popular alternative to HFSM
- In search of the "Mythical HFSMBTH" – HFSM-BT Hybrid
  - from a 2017 Game Developers conference talk by Bobby Anguelov https://www.youtube.com/watch?v=Qq_xX1JCreI&t=1159s
  - Combine each method's strengths
    - BT: Reactive decisions, high-speed
    - HFSM: cyclical/repetitive behaviors , collaborative autonomy
- Flexible Behavior Trees : The "Mythical HFSMBTH" with FlexBE
    - The paper: https://arxiv.org/abs/2203.05389
    - The code: https://github.com/FlexBE/flexible_behavior_trees
    - The demo: https://github.com/FlexBE/flex_bt_turtlebot3_demo

Flexible Manipulation

- FlexBE interface to MoveIt!

  https://ieeexplore.ieee.org/document/8478933

  https://github.com/CNURobotics/flexible_manipulation

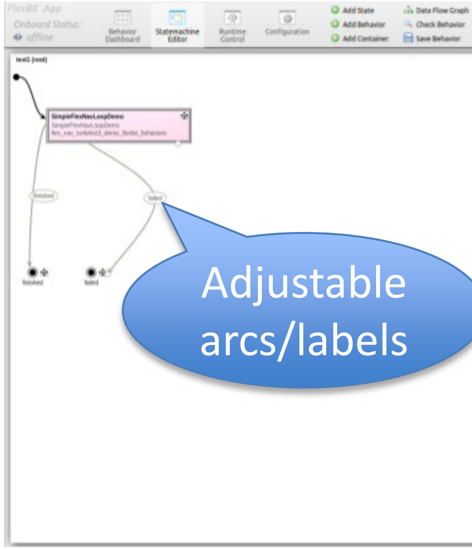
- Currently only ROS 1 (Kinetic) and Python 2
- Planning for ROS 2 conversion late 2024
  - MoveIt! 2 stabilizing
  - Stable ROS 2 physics-based simulations of robot arms

Ongoing Research and Development

Ongoing Research and Development

System Improvements

- Testing, demonstrations, and tutorials for packages
- FlexBE WebUI
  - Improved graphics
  - Simplified Python comms integration with UI
  - Expect alpha pre-release January 2024
  - Planned UI Advancements
    - Improved operator control over concurrent states
    - HFSM Synthesis and debugging tools



Supported under Naval Engineering Education Consortium (NEEC) grant N00174-23-1-0018

HFSM Synthesis in FlexBE

- Designing HFSM (or BT) is hard
  - Requires significant testing and validation
- Goal: “Correct-by-construction” synthesis tools
  - Specialized research in formal methods community
  - Less accessible to general robotics community

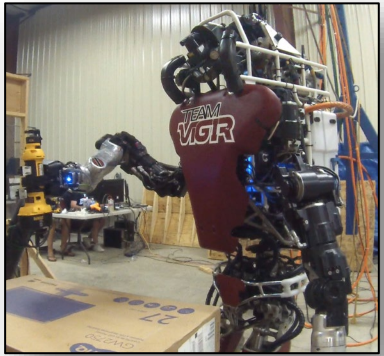
Prior Work with ROS 1 FlexBE and Reactive GR1 Synthesis

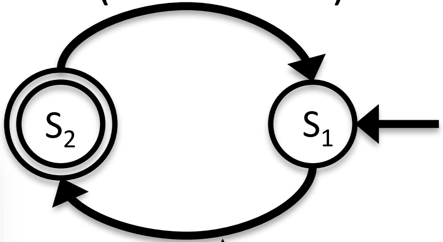
Formal Task Specification

- Workspace
- System
- Environment

→ Reactive Synthesis → Discrete Strategy (Automaton)

$$(\varphi_i^a \wedge \varphi_s^a \wedge \varphi_l^a) \rightarrow (\varphi_i^g \wedge \varphi_s^g \wedge \varphi_l^g)$$





Grounding to System Capabilities

(e.g. FlexBE state implementations)

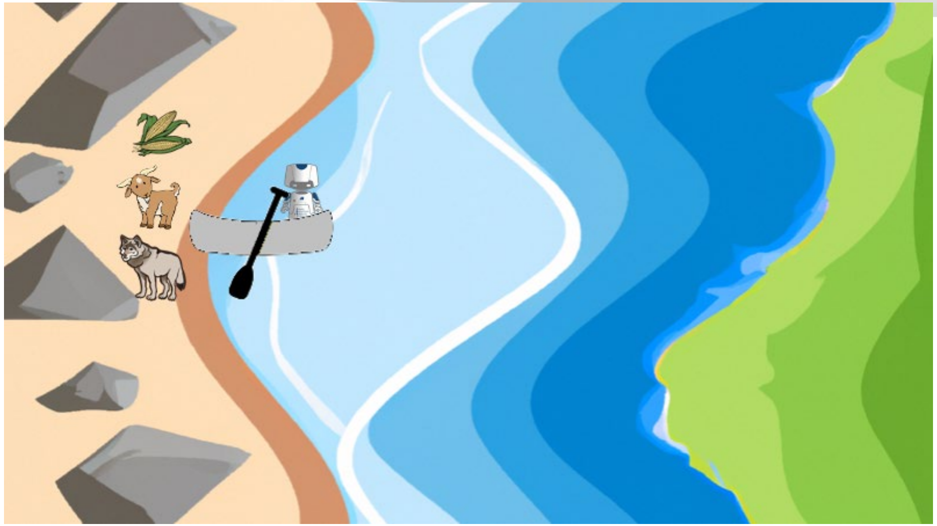
Maniatopoulos *et al.*, "Reactive high-level behavior synthesis for an Atlas humanoid robot," *ICRA 2016*, https://ieeexplore.ieee.org/document/7487613

Hayhurst and Conner, "Towards Capability-Based Synthesis of Executable Robot Behaviors," *SoutheastCon 2018*, St. Petersburg, FL, USA, 2018, pp. 1-8, https://ieeexplore.ieee.org/document/8479047

VERIFIABLE ROBOTICS RESEARCHGROUP

TEAM VIGR

GR1 Synthesis Example w/ Slugs



“If in next step the goat and wolf are on the left bank, then on the next step the farmer better be on left bank”

`X(!goat & !wolf) -> X!farmer`

https://link.springer.com/chapter/10.1007/978-3-319-41540-6_18

Assumptions → Guarantees

$$(\varphi_i^a \wedge \varphi_s^a \wedge \varphi_l^a) \rightarrow (\varphi_i^g \wedge \varphi_s^g \wedge \varphi_l^g)$$

GR1 fragment of LTL complexity $O(2^n)$

vs.

Full LTL w/ $O(2^{2^n})$

time →

wolf	·	·	·	●	●	●	●	●
goat	·	●	●	●	·	·	·	●
corn	·	·	·	·	·	●	●	●
farmer	·	●	·	●	·	●	·	●
move_wolf	·	·	●	·	·	·	·	·
move_goat	●	·	·	●	·	·	●	·
move_corn	·	·	·	·	●	·	·	·
move_farmer	·	●	·	·	·	●	·	·
(!goat & move_goat & !farmer) -> (Xgoat & Xfarmer)	●	●	●	●	●	●	●	●
!move_wolf -> ((wolf & Xwolf) | (!wolf & !Xwolf))	●	●	●	●	●	●	●	●
(corn & !farmer) -> !move_corn	●	●	●	●	●	●	●	●

Ongoing Synthesis Work in FlexBE

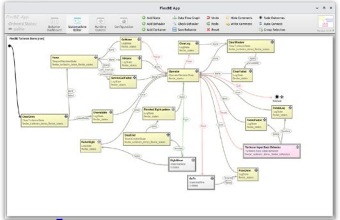
- Converting 2018 system into ROS 2 version ☑
- Develop several tutorials and demonstrations
  - Make synthesis more accessible to general community

The paper: coming Spring '24
The code: coming Dec '23
The demo: coming Dec '23

- Refactor and redesign to simplify usage
- Integrate automatic discovery of system capabilities

New work supported under Naval Engineering Education Consortium (NEEC) grant N00174-23-1-0018

Conclusion



- FlexBE is now available for ROS 2
- Quick start demo at https://github.com/FlexBE/flexbe_turtlesim_demo
- Available extension packages
- Development is active and ongoing
- Active research integrating HFSM synthesis

For more information
robotics@cnu.edu

FlexBE State Implementations

- Each state corresponds to a Python implementation of the **`EventState`** class

  https://github.com/FlexBE/flexbe_behavior_engine/blob/ros2-devel/flexbe_core/flexbe_core/core/event_state.py

  - **`on_start`** – invoked when behavior initialized
  - **`on_enter`** – invoked when state becomes active
  - **`execute`** – invoked at (approximately) specified rate
  - **`on_exit`** – invoked when state returns outcome
  - **`on_stop`** – invoked when behavior is shutdown
  - **`on_pause/resume`** – invoked when state is locked/unlocked

FlexBE in Education

- Currently use in CPSC 472/572 "Introduction to Robotics"@CNU
- FlexBE in low-autonomy acts as "script"
  - "Get goal", "Plan path", "Execute path follower"
  - Allows users to better see interaction of components
- Teach HFSM-based behavior control
  - Students can write Python-based state implementations
  - Use FlexBE to control high level system behaviors
  - Reinforce use of object-oriented paradigm

WGCF Specs (Slugs format)

[INPUT]

our farmer prefers 4 letter words not cabbages

goat

wolf

corn

farmer

[OUTPUT]

move_goat

move_wolf

move_corn

move_empty

[ENV_INIT]

Everyone on the left bank

!goat

!wolf

!corn

!farmer

[SYS_INIT]

The game solver should figure out that one thing needs
to be moved initially

[ENV_TRANS]

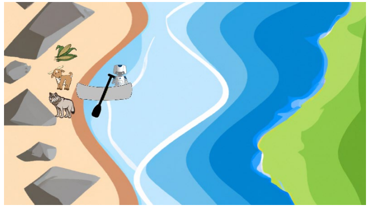
What occurs in environment

transitions due to move

(!goat & move_goat & !farmer) -> (goat' & farmer')

(goat & move_goat & farmer) -> (!goat' & !farmer')

$$(\varphi_i^a \wedge \varphi_s^a \wedge \varphi_l^a) \rightarrow (\varphi_i^g \wedge \varphi_s^g \wedge \varphi_l^g)$$



(wolf & move_wolf & farmer) -> (!wolf' & !farmer')

(!wolf & move_wolf & !farmer) -> (wolf' & farmer')

(corn & move_corn & farmer) -> (!corn' & !farmer')

(!corn & move_corn & !farmer) -> (corn' & farmer')

(move_empty & farmer) -> !farmer'

(move_empty & !farmer) -> farmer'

Not moving leaves the environment alone

!move_goat -> ((goat & goat') | (!goat & !goat'))

!move_wolf -> ((wolf & wolf') | (!wolf & !wolf'))

!move_corn -> ((corn & corn') | (!corn & !corn'))

WGCF Spec (continued)

[SYS_TRANS]

Allowable commands from our controller

Can only move one thing at a time

!(move_goat & move_wolf)

!(move_goat & move_corn)

!(move_goat & move_empty)

!(move_corn & move_wolf)

!(move_corn & move_empty)

!(move_wolf & move_empty)

What we need our controller to enforce

Farmer must stay when goat and corn are together

(goat' & wolf') -> farmer'

(!goat' & !wolf') -> !farmer'

(goat' & corn') -> farmer'

(!goat' & !corn') -> !farmer'

Cannot move unless boat on same side

(goat & !farmer) -> !move_goat

(!goat & farmer) -> !move_goat

(wolf & !farmer) -> !move_wolf

(!wolf & farmer) -> !move_wolf

(corn & !farmer) -> !move_corn

(!corn & farmer) -> !move_corn

[ENV_LIVENESS]

Nothing

[SYS_LIVENESS]

Let's get across infinitely often

goat & wolf & corn

$$(\varphi_i^a \wedge \varphi_s^a \wedge \varphi_l^a) \rightarrow (\varphi_i^g \wedge \varphi_s^g \wedge \varphi_l^g)$$