

High-level Behavior Synthesis for an ATLAS Humanoid Robot

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Abstract—In this paper we ...

Body of my TODO example

LIST OF TODOS, FIXES, OPEN ISSUES

Title of my TODO example (hyperlink)	1
Co-authors should review and fix contact info . .	1
Consider mutex for grounding conflicts in this paper?	1
Make FlexBE and Synthesis notation consistent .	2
Mathematical properties of mapping \mathcal{D}_M	2
Mention absence of workspace in \mathcal{D}	2
Activation–Outcomes or just Completion-Failure ?	3
Explicit “solution” to Problem 1	3
Mapping multiple outcomes to one proposition . .	3
How to write Outcome MutEx formula (slugs) . .	3
Procedure for recursively adding preconditions . .	4
How to write control mode MutEx formula (slugs)	4
Where to state memory initial conditions ?	4
Comment on savings of single liveness requirement ?	5
Properly mention SLUGS’ fragment	5
Update ROS packages figure	5
Synthesis time as a function to number of actions ?	6
Show generated LTL formulas for synthesis demo	6



Fig. 1: Team ViGIR’s ATLAS humanoid robot on the first day of the DRC Finals. (Photo credit: DARPA)

I. INTRODUCTION

...

Example 1: Consider the high-level task: “Walk to the valve and turn it” (Fig. 1). This would be an intuitive way to express the task from a non-expert user’s point-of-view. However, ... (not formal, preconditions, templates, reaction to failures, etc.)

Contributions (brain dump):

- Partial to full specification
 - Most intuitive from the users point-of-view
 - Limited message size over bad comms (send partial specification → compile and synthesize onboard)
- Multi-paradigm specification (objectives and initial conditions from user, topology/modes, preconditions, task)

Also consider mutex for grounding conflicts?

- Generalization of activation–completion paradigm [1]
- Integration with FlexBE and ROS
- Experimental validation on ATLAS

Literature Survey:

- Vasu’s “fast-slow” paradigm [1]
- Alternatives to GR(1) Synthesis
 - STRIPS-type planners
 - Optimization-based LTL synthesis (Eric Wolff et al.)
 - **co-safe LTL** (Lydia Kavraki, Calin Belta, etc.)

II. PRELIMINARIES

A. ATLAS Humanoid Robot

... Humanoid by Boston Dynamics (see Fig. 1), ..., BDI control modes (aka “behaviors”), control mode dictates

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Each author should review and fix their contact info.

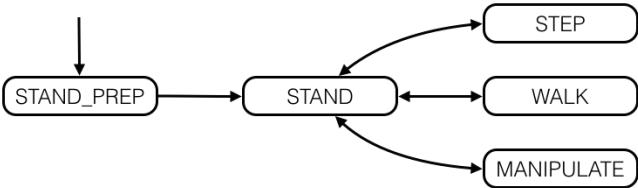


Fig. 2: Excerpt from the BDI control mode interface. Some changes between modes are unidirectional while others are bidirectional. After the initial checkout, ATLAS is in the STAND_PREP control mode.

which joints are controlled by the low-level controllers and which joints the developers can control (see Fig. 2).

B. Team ViGIR's Approach

1) Something: ... [2], [3] ... Briefly touch on our software approach [4], especially control modes and templates [5]. Just enough for the “High-level Control” subsection and the experimental demos to make sense.

Define *system* as ATLAS plus Team ViGIR software.

2) *High-level Control*: ... SMACH [6], Behavior control [7], [8] FlexBE¹, GUI², behaviors and states³.

Some incomplete notes from Philipp's work. Not sure yet how much detail is needed here.

Philipp's definitions differ slightly from the synthesis literature. Ensure that we end up with consistent notation.

- A primitive $p \in P$ is any atomic capability of the robot.
 - A state $s \in S$ interfaces functionality with behaviors, where the set of all state implementations S includes states based on primitives $S_p \subseteq S$. Each state defines outcomes s_{Oc} and execution of a state is terminated by returning one outcome matching the result of execution $oc \in s_{Oc}$.
 - A state machine SM composes a set of states S_{SM} , where each state $s(i) \in S_{SM}$ is the instantiation of a state implementation $s \in S$.
 - Each state machine SM defines userdata D_{SM}
 - A behavior B is implemented by its state machine B_{SM} .

Example: Fig. 3 ... designed manually by Team ViGIR developers using the FlexBE Editor (graphical user interface).

C. Linear Temporal Logic and Reactive LTL Synthesis

... Atomic propositions, LTL, environment vs system, etc.

GR(1) formulas φ have an assume-guarantee structure between the environment (e) and the system (s):

$$\begin{aligned}\varphi &= (\varphi_e \Rightarrow \varphi_s), \\ \varphi_e &= \varphi_e^i \wedge \varphi_e^t \wedge \varphi_e^g, \\ \varphi_s &= \varphi_s^i \wedge \varphi_s^t \wedge \varphi_s^g,\end{aligned}\tag{1}$$

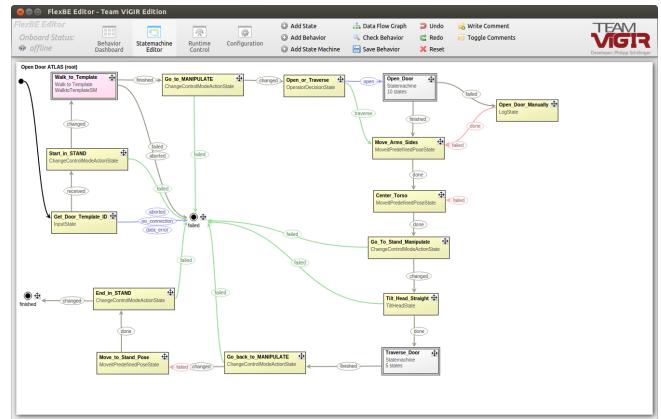


Fig. 3: A manually designed high-level behavior for carrying out the DRC Finals’ “Door” task. The initial state is indicated by the black arrow originating from the top left. The state machine has two outcomes, “finished” (bottom left) and “failed” (center). It is a hierarchical state machine; yellow states are primitives, gray states are state machines, and purple states are other behaviors embedded in this one.

where the superscript i denotes initial conditions, t safety assumptions/requirements, and g liveness assumptions/requirements (goals) for the environment and the system, respectively.

GR(1) Synthesis [10] ...

III. PROBLEM STATEMENT

Problem 1 (Discrete Abstraction): Given ATLAS' control mode transition constraints and the available actions \mathcal{A} , define a discrete abstraction \mathcal{D} of the robot-plus-software system, S , that captures the execution and outcomes of the atomic capabilities (control mode transitions and actions). In addition, maintain a mapping, $\mathcal{D}_M : S \rightarrow AP$, between the atomic capabilities of the system S and the corresponding elements of the discrete abstraction, $\pi \in AP$.

In practice, the mapping \mathcal{D}_M is not one-to-one. But we can treat it as one-to-one to simplify things for the paper.

In general, we would have included the robot's workspace in \mathcal{D} . However, that was not necessary in the context of the DRC. Mention in footnote?

Problem 2 (Formal Task Specification): Given a task in terms of goals \mathcal{G} , the task's initial conditions \mathcal{I} , and the discrete abstraction \mathcal{D} of the system S that is to carry out the task, automatically generate a specification \mathcal{T}_S that encodes, in a formal language, the task being carried out by S .

Problem 3 (Behavior Synthesis): Given a formal task specification, \mathcal{T}_S , and the mapping \mathcal{D}_M , automatically generate a software implementation of a discrete, high-level, control strategy that is verifiably guaranteed to satisfy \mathcal{T}_S .

Revisiting Example 1, we could say that the task's goals G are $\{\text{approach_valve}, \text{turn_valve}\}$ and the initial conditions I are, e.g., $\{\text{STAND}\}$

¹https://github.com/team-viqir/flexbe_behavior_engine

²https://github.com/team-vigir/flexbe_chrome_app

³https://github.com/team-vigir/vigir_behaviors

IV. DISCRETE ABSTRACTION

A. Control Modes & Actions

We model ATLAS' control mode interface (c.f. Fig. 2) as a transition system $(\mathcal{M}, \rightarrow)$, where \mathcal{M} is the set of states, each corresponding to one control mode, $m \in \mathcal{M}$, and \rightarrow is a set of valid control mode transitions (subset of $\mathcal{M} \times \mathcal{M}$). In addition, we define $Adj(m) = \{m' \in \mathcal{M} \mid (m, m') \in \rightarrow\}$ and also allow self-transitions, i.e., $m \in Adj(m), \forall m \in \mathcal{M}$.

Furthermore, ATLAS can perform actions. Each action, $a \in \mathcal{A}$, corresponds to an atomic capability of the system, e.g., generation of a footstep plan or closing the robot's fingers. Actions may also have one or more preconditions. Action preconditions can be control modes or other actions, i.e., $Prec(a) \in 2^{(\mathcal{A} \cup \mathcal{M})}$, $a \notin Prec(a), \forall a \in \mathcal{A}$.

B. Atomic Propositions

Write LTL formulas in terms of any possible outcome, $o \in Out(a)$, or only of completion and failure, $\{c, f\}$

We adopt a paradigm that generalizes the one in [1]. We abstract the discrete actions, $a \in \mathcal{A}$, that ATLAS can perform using one system proposition, π_a , per action and one environment proposition, π_a^o , per possible outcome of that action, $o \in Out(a)$. Similarly,⁴ for each control mode, $m \in \mathcal{M}$, we have a system proposition π_m and a number of outcome propositions π_m^o . For both actions and control mode transitions, the outcomes that are of most interest in the context of this paper are completion (c) and failure (f) of the action. That is, $Out(a) = Out(m) = \{c, f\}$. Therefore, the set of atomic propositions AP is given by Eq. (2):

$$\mathcal{Y} = \bigcup_{a \in \mathcal{A}} \pi_a \bigcup_{m \in \mathcal{M}} \pi_m, \quad (2a)$$

$$\mathcal{X}' = \mathcal{X} \bigcup_{a \in \mathcal{A}} \bigcup_{o \in Out(a)} \pi_a^o \bigcup_{m \in \mathcal{M}} \bigcup_{o \in Out(m)} \pi_m^o, \quad (2b)$$

where \mathcal{X} are environment propositions other than outcome propositions, e.g., ones that abstract sensors, as per [9].

C. Proposition Grounding / Mapping

Now that we have props, show what \mathcal{D}_M looks like.

Comment on the possibility of mapping multiple outcomes to one proposition, since it appears in Fig. 6a

V. FORMAL TASK SPECIFICATION

A. Multi-Paradigm Specification

Specifying a robot task in a formal language can be time consuming and error prone. It also requires an expert user. To alleviate these issues, we employ a multi-paradigm specification approach. We first observe that there are portions of the task specification \mathcal{T}_S that are going to be system-specific and portions that are going to be task-specific, such as the task's goals. Intuitively, a user should only have to specify the

⁴The distinction between action and control mode propositions is purely for the sake of clarity of notation. There is nothing special about either.

goals without worrying about the internals of the robot and the software it is running. For ATLAS, we can automatically infer which control modes and actions are pertinent to a task. Finally, the initial conditions are either specified by the user or detected at runtime.

Referring to Problem 2, we get the goals, \mathcal{G} , and initial conditions, \mathcal{I} , from the user. The discrete abstraction, \mathcal{D} , is ATLAS-specific and we assume that it has been created a priori from expert developers, according to Section IV. We can now automatically compile the task specification \mathcal{T}_S in (the GR(1) fragment [10] of) Linear Temporal Logic. Since LTL is compositional, we can generate individual LTL formulas and then conjunct them to get the full LTL specification.

B. Specification of Actions and Control Mode Constraints

1) *Generic Formulas*: We say that an activation proposition π_p , $p \in \{a, m\}$, is True when the corresponding primitive functionality is being activated and False when it is not being activated⁵. Therefore, the system safety requirement (3) dictates that all activation propositions $\pi_p \in \mathcal{Y}$ should turn False once an outcome has been returned.

$$\bigwedge_{o \in Out(p)} \square (\pi_p \wedge \bigcirc \pi_p^o \Rightarrow \bigcirc \neg \pi_p) \quad (3)$$

The environment safety assumption (4) dictates that the outcomes, π_p^o , of the activation of any primitive functionality p are mutually exclusive. For example, an action cannot both succeed and fail. Formula (4) also allows for no outcome being True.

Formula (4) requires the \bigcirc operators to synthesize properly (slugs), but intuitively, they shouldn't be there.

$$\bigwedge_{o \in Out(p)} \square (\bigcirc \pi_p^o \Rightarrow \bigwedge_{o' \neq o} \bigcirc \neg \pi_p^{o'}) \quad (4)$$

The environment safety assumption (5) constraints the value of outcomes. Specifically, it dictates that, if an outcome is False and the corresponding primitive functionality is not being activated, then that outcome should remain False. It is a generalization of formula (4) in [1].

$$\bigwedge_{o \in Out(p)} \square (\neg \pi_p^o \wedge \neg \pi_p \Rightarrow \bigcirc \neg \pi_p^o) \quad (5)$$

2) *Action-specific Formulas*: The following formulas encode the connection between the activation and the possible outcomes of the robot's actions, $a \in \mathcal{A}$.

The environment safety assumptions (6) dictate that the value of an outcome should not change if the corresponding action has not been activated again. In other words, outcomes persist.

$$\bigwedge_{o \in Out(a)} \square (\pi_a^o \wedge \neg \pi_a \Rightarrow \bigcirc \pi_a^o) \quad (6)$$

⁵Note that this is in contrast to [1], where π_p being False stands for the primitive functionality p being deactivated, e.g., turning a camera off.

The environment liveness assumption (7) is a fairness condition. It states that (always) eventually, the activation of an action will result in an outcome. The disjunct $\neg\pi_a$ is added in order to prevent the system from winning the game by never activating the action.

$$\square \diamond (\left(\pi_a \wedge \bigvee \circ \pi_a^o \right) \vee \neg\pi_a) \quad (7)$$

The system safety requirement (8) demonstrates how a formula encoding the preconditions of an action, $Prec(a)$, looks like in the activation–outcomes paradigm.

Demonstrate how, given partial specification, we can bring in only those actions and modes that are necessary.

$$\square \left(\bigvee_{p \in Prec(a)} \neg\pi_p^c \Rightarrow \neg\pi_a \right) \quad (8)$$

where the superscript $c \in Out(p)$ stands for “completion”.

3) *Control Mode Formulas*: For brevity of notation, let

$$\varphi_m = \pi_m \wedge \bigwedge_{m' \neq m} \neg\pi_{m'}$$

Activating φ_m , as opposed to π_m , takes into account the mutual exclusion between control modes $m \in \mathcal{M}$. Also let

$$\varphi_{\mathcal{M}}^{none} = \bigwedge_{m \in \mathcal{M}} \neg\pi_m,$$

where $\varphi_{\mathcal{M}}^{none}$ being True stands for not activating any control mode transitions, i.e., staying in the same control mode.

The system safety requirements (9) encode a topological transition relation, such as the BDI control mode transition system.

$$\bigwedge_{m \in \mathcal{M}} \square \left(\bigcirc \pi_m^c \Rightarrow \bigvee_{m' \in Adj(m)} \bigcirc \varphi_{m'} \vee \bigcirc \varphi_{\mathcal{M}}^{none} \right) \quad (9)$$

The environment safety assumptions (10) enforce mutual exclusion between the BDI control modes.

Formula (10) also requires the \bigcirc operators to synthesize properly (slugs), but intuitively, they shouldn't be there.

$$\bigwedge_{m \in \mathcal{M}} \square \left(\bigcirc \pi_m^c \Leftrightarrow \bigwedge_{m' \neq m} \bigcirc \neg\pi_{m'}^c \right) \quad (10)$$

The environment safety assumptions (11) govern how the active control mode can change in a single time step in response to the activation of a control mode transition.

$$\bigwedge_{m \in \mathcal{M}} \bigwedge_{m' \in Adj(m)} \square \left(\pi_m^c \wedge \varphi_{m'} \Rightarrow \left(\bigcirc \pi_m^c \bigvee_{o \in Out(m')} \bigcirc \pi_{m'}^o \right) \right) \quad (11)$$

The environment safety assumptions (12) dictate that the value of the outcomes of control mode transitions must not change if no transition is being activated, i.e., they must persist.

$$\bigwedge_{m \in \mathcal{M}} \bigwedge_{o \in Out(m)} \square \left(\pi_m^o \wedge \varphi_{\mathcal{M}}^{none} \Rightarrow \bigcirc \pi_m^o \right) \quad (12)$$

The environment liveness assumption (13) is the equivalent of the fairness condition (7) for control mode transitions. This single formula accounts for all control modes.

$$\square \diamond \left(\bigvee_{m \in \mathcal{M}} \left(\varphi_m \wedge \bigvee_{o \in Out(m)} \bigcirc \pi_m^o \right) \vee \varphi_{\mathcal{M}}^{none} \right) \quad (13)$$

C. Specification of Initial Conditions

For each action, a , and control mode, m , in the initial conditions, \mathcal{I} , the completion proposition should be True in the environment initial conditions (14). All other outcome propositions corresponding to those actions and control modes, as well as all outcome propositions corresponding to any other actions and control modes, should be False.

$$\varphi_i^e = \bigwedge_{i \in \mathcal{I}} \left(\pi_i^c \bigwedge_{o \in Out(i) \setminus \{c\}} \neg\pi_i^o \right) \wedge \bigwedge_{j \notin \mathcal{I}} \bigwedge_{o \in Out(j)} \neg\pi_j^o \quad (14)$$

Activation propositions are False regardless of whether that action or control mode is in the initial conditions or not (15). The reason being that, intuitively, if we want something to be an initial condition, then we shouldn't have the resulting controller re-activate it at the beginning of execution.

$$\varphi_i^s = \bigwedge_{i \in \mathcal{I}} \neg\pi_i \wedge \bigwedge_{j \notin \mathcal{I}} \neg\pi_j \quad (15)$$

Do I move ICs to the end of the section and include memory props explicitly? Or leave them here, but state memory ICs along with “infinite-to-finite” formulas?

D. Specification of Task Goals

The system initial condition (16), safety requirements (17) and (18), and liveness requirement (19) are used to reason about the satisfaction of the system's goals, $g \in \mathcal{G}$, in a finite run (as opposed to infinite execution, which is what LTL is defined over). In this finite run paradigm, the synthesized state machine (SM) itself has outcomes, $o \in Out(SM)$. The propositions corresponding to the SM's outcomes, π_{SM}^o , are system, not environment, propositions. The system propositions, μ_g , serve as memory of having accomplished each goal (c.f. [11]).

$$\bigwedge_{g \in \mathcal{G}} \neg\mu_g \quad (16)$$

$$\bigwedge_{g \in \mathcal{G}} \square \left(\bigcirc \pi_g^c \vee \mu_g \Leftrightarrow \bigcirc \mu_g \right) \quad (17)$$

$$\square \left(\pi_{SM}^c \Leftrightarrow \bigwedge_{g \in \mathcal{G}} \mu_g \right) \quad (18a)$$

$$\square \left(\pi_{SM}^f \Leftrightarrow \bigvee_{\pi \in \mathcal{Y}} \pi^f \right) \quad (18b)$$

$$\bigwedge_{o \in Out(SM)} \square \left(\pi_{SM}^o \Rightarrow \bigcirc \pi_{SM}^o \right) \quad (18c)$$

$$\square \diamond (\bigvee_{o \in Out(SM)} \pi_{SM}^o) \quad (19)$$

The time complexity of synthesis is cubic in the number of liveness requirements. We save by only having one. Although that's probably dominated by the complexity being exponential in the number of propositions.

Formula (17) does not guarantee that the goals will be achieved in a specific order. However, that is often desirable. To this end, we can define the goals as an ordered set $\mathcal{G} = \{g_1, g_2, \dots, g_n\}$, where $g_i < g_j$ for $i < j$, and the relation $g_i < g_j$ means that goal g_i has to be achieved before g_j . With this definition, we can replace the safety requirement (17) with (20), whenever strict goal order is desired.

$$\bigwedge_{i=1}^n \square ((\pi_{g_i} \wedge \bigcirc \pi_{g_i}^c) \wedge \mu_{g_{i-1}} \vee \mu_{g_i} \Leftrightarrow \bigcirc \mu_{g_i}), \quad (20)$$

where $\mu_{g_0} \triangleq \text{True}$. Formula (20) forces the system to carry out goal g_i after it has accomplished goal g_{i-1} . It can still activate the action corresponding to π_{g_i} earlier, as necessitated by other parts of the task, but that will not count towards achievement of g_i , as indicated by μ_{g_i} being True.

Finally, these auxiliary (memory and SM outcome) propositions have to be added to the system propositions:

$$\mathcal{Y}' = \mathcal{Y} \bigcup_{g \in \mathcal{G}} \mu_g \bigcup_{o \in Out(SM)} \pi_{SM}^o$$

VI. HIGH-LEVEL BEHAVIOR SYNTHESIS

We tackle Problem 3 in two sequential steps. First, we automatically generate a correct-by-construction automaton from the formal specification \mathcal{T}_S using GR(1) synthesis (see [10] and Section II-C). Specifically, we employ the synthesis algorithm in [12], which can handle a slightly larger fragment of LTL than GR(1). Namely, the one that includes \bigcirc (next) operators in liveness formulas, such as in formulas (7) and (13). This algorithm was first used in [1].

@HKG, is it true that Vasu's paper was the first case of synthesis for this fragment? Had Ruediger used it before?

Second, we use the mapping $\mathcal{D}_M^{-1} : AP \rightarrow S$ to instantiate the abstract automaton as a concrete software implementation, i.e., an executable state machine in the SMACH/FlexBE framework (see Section II-B.2).

VII. ROS IMPLEMENTATION

We have implemented all aspects of our approach in `vigir_behavior_synthesis`,⁶ a collection of Robot Operating System (ROS) Python packages. Figure 4 depicts these packages as well as the nominal workflow.

The synthesis action server (`vigir_synthesis_manager`) receives a request from the user via FlexBE's GUI. Given the user's input (initial conditions and goals), the server first requests a full set of LTL formulas for ATLAS from

⁶https://github.com/team-vigir/vigir_behavior_synthesis

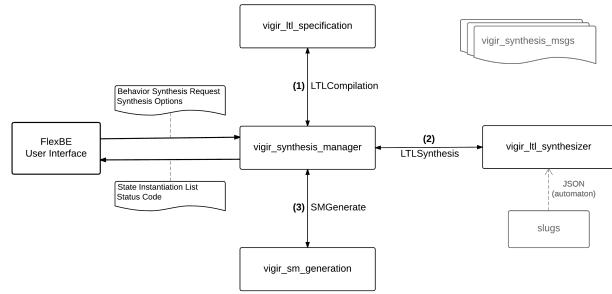


Fig. 4: Team ViGIR's “Behavior Synthesis” ROS packages and the nominal workflow (clockwise, starting from the left).

- (i) Add ReSpeC to the image (move msgs to the left)
- (ii) Either number all arrows or none (iii) If I end up renaming LTLCompilation srv, update image accordingly.

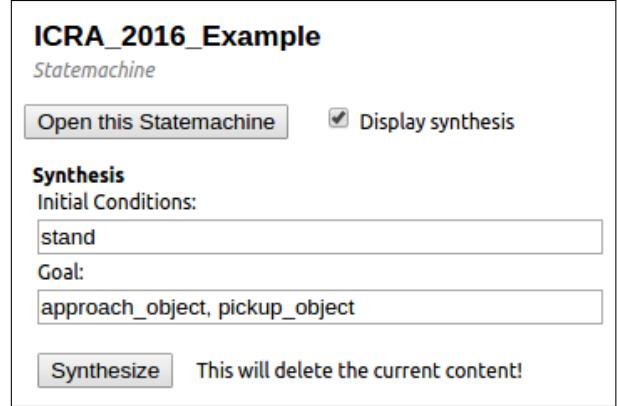


Fig. 5: Screenshot of the FlexBE Editor's synthesis menu.

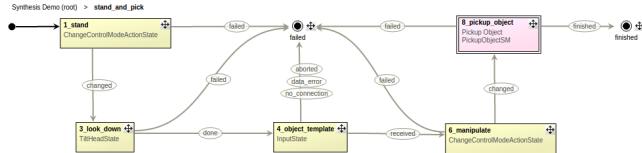
the LTL Compilation service (`vigir_lt1_specification`). The generation of the LTL formulas from Section V is delegated to our “Reactive Specification Construction kit,” which is a ROS-independent Python framework⁷.

The LTL Synthesis service (`vigir_lt1_synthesizer`) acts as a wrapper for an external synthesis tool (currently, [12] is supported). Upon request, it returns an automaton that is guaranteed to satisfy the LTL specification, if one exists. Finally, the server requests a state instantiation message from the State Machine Generation service (`vigir_sm_generation`). The resulting message contains instructions that FlexBE can use to generate Python code: an executable state machine that instantiates the synthesized automaton. The corresponding action, services, and messages are defined in the `vigir_synthesis_msgs` package.

The following excerpt⁸ is from the State Instantiation list message, which is the end product of `vigir_behavior_synthesis` (see Fig. 4). Specifically, this excerpt corresponds to the primitive `object_template`, which appears in Fig. 6a. This message provides the FlexBE

⁷<https://github.com/team-vigir/ReSpeC>

⁸We have omitted some details for the sake of brevity and clarity of presentation. For example, most list elements are strings, e.g., "template_id".



(a) The state machine synthesized for the task $\mathcal{I} = \{\text{stand_prep}\}$ and $\mathcal{G} = \{\text{look_down}, \text{pickup_object}\}$.



(b) ...

Fig. 6: These correspond to the first part of the video attachment.

Editor with sufficient information to generate Python code.

```
state-path: /4.object_template
state-class: InputState
parameter-names: [request]
parameter-values: [InputState.SELECTED_OBJECT_ID]
outcomes: [no_connection, aborted, received, data_error]
transitions: [failed, failed, 6_manipulate, failed]
autonomy: [0]
userdata-keys: [data]
userdata-remapping: [template.id]
```

VIII. EXPERIMENTAL VALIDATION

... Also see video attachment

Provide data on how computationally costly/cheap behavior synthesis is. Time vs number of actions?

A. Synthesis from scratch

“synthesis_pickup_8” demo ...

Upload the full LTL specification for the “stand and pick” demo online and add link?

B. Synthesis on-the-fly

“synthesis_runtime_4” demo ...

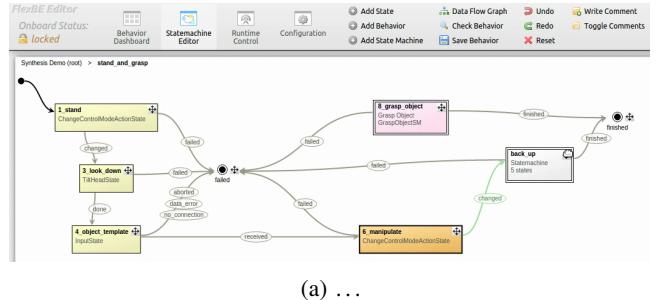
IX. CONCLUSIONS AND FUTURE WORK

...

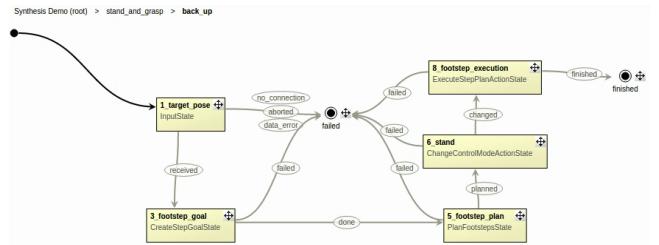
... Capability specification, integrate more robots, ...

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The authors thank all other members of Team ViGIR and especially Alberto Romay, Stefan Kohlbrecher, and Prof. Oskar von Stryk from Technische Universität Darmstadt.



(a) ...



(b) The state machine was synthesized from $\mathcal{I} = \{\text{manipulate}\}$ and $\mathcal{G} = \{\text{footstep_execution}\}$.

Fig. 7: Snapshots from ... They correspond to the second part of the video attachment.

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