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Temporally and spatially flexible plan execution for dynamic hybrid systems

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ABSTRACT

Planners developed in the Artificial Intelligence community assume that tasks in the task plans they generate will be executed predictably and reliably. This assumption provides a useful abstraction in that it lets the task planners focus on what tasks should be done, while lower-level motion planners and controllers take care of the details of how the task should be performed. While this assumption is useful in many domains, it becomes problematic when controlling physically embedded systems, where there are often delays, disturbances, and failures. The task plans do not provide enough information about allowed flexibility in task duration and hybrid state evolution. Such flexibility could be useful when deciding how to react to disturbances. An important domain where this gap has caused problems is robotics, particularly, the operation of robots in unstructured, uncertain environments. Due to the complexity of this domain, the demands of tasks to be performed, and the actuation limits of robots, knowledge about permitted flexibility in execution of a task is crucial. We address this gap through two key innovations. First, we specify a *Qualitative State Plan* (QSP), which supports representation of spatial and temporal flexibility with respect to tasks. Second, we extend compilation approaches developed for temporally flexible execution of discrete activity plans to work with hybrid discrete/continuous systems using a recently developed Linear Quadratic Regulator synthesis algorithm, which performs a state reachability analysis to prune infeasible trajectories, and which determines optimal control policies for feasible state regions. The resulting *Model-based Executive* is able to take advantage of spatial and temporal flexibility in a QSP to improve handling of disturbances. Note that in this work, we focus on execution of QSPs, and defer the problem of how they are generated. We believe the latter could be accomplished through extensions to existing task planners.

1. Introduction

The Computer Science, and particularly, Artificial Intelligence fields have fruitfully operated for decades using a “digital abstraction” in which instructions are assumed to execute predictably and reliably. Historically, the planning community began with a similar abstraction, using an action representation in which state is directly observable and controllable, and in which effects are deterministic and predictable. This is the case, for example, with PDDL (Planning Domain Definition Language) generative planners [1]. In reality, however, when controlling physically embedded systems, there are often delays, disturbances, and failures. Thus, there is a gap between the capabilities of such planners and plan executives, and the

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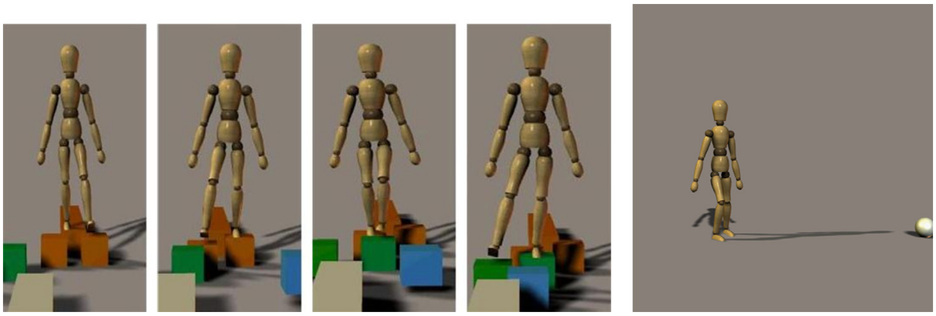

(a) (b)

Fig. 1. Plan execution systems for humanoid robot tasks such as walking on constrained terrain, or kicking a soccer ball, must take into account both the demanding requirements of the task, and also, the actuation limits of the robot.

requirements for controlling physical systems. Specifically, the task plans generated by these planners do not provide enough information about allowed flexibility in task duration and hybrid state evolution. Such flexibility could be useful to a plan executive when deciding how to react to disturbances.

While there are applications where the gap can be ignored, this is generally only the case in systems that are easy to control. An important domain where this gap has caused problems is robotics, particularly, the operation of robots in unstructured, uncertain environments. Due to the complexity of this domain, the demands of tasks to be performed, and the actuation limits of robots, knowledge about permitted flexibility in execution of a task is crucial. We address this gap through two key innovations. First, we specify a *Qualitative State Plan* (QSP), which supports representation of spatial and temporal flexibility with respect to tasks. Second, we extend compilation approaches developed for temporally flexible execution of discrete activity plans to work with hybrid discrete/continuous systems using a recently developed Linear Quadratic Regulator synthesis algorithm, which performs a state reachability analysis to prune infeasible trajectories, and which determines optimal control policies for feasible state regions. The resulting *Model-based Executive* is able to take advantage of spatial and temporal flexibility in a QSP to improve handling of disturbances. Note that in this work, we focus on execution of QSPs, and defer the problem of how they are generated. The latter can be accomplished through extensions to existing task planners [2].

The temporal planning and execution community has addressed the issues of plan execution delays and disturbances in the context of time-critical, embedded missions, such as planetary fly bys [3]. In these systems, temporal disturbances are compensated for reactively by generating least-commitment temporal plans to offer temporal flexibility to the scheduler, and by scheduling execution times dynamically, as disturbances are observed. This provides a significant improvement in capabilities, but the gap still exists because in these systems, the controllers do not know about the plans in which they are used, and the planners do not know about the details of the controllers that implement their operations. When generating plans for robotic systems, such as humanoid robots (Fig. 1) or autonomous aerial vehicles, coupling between control actions and the continuous state of the robot is significant; the physical dynamics and actuation limits of the robot affect plan and schedule feasibility. Conversely, the controllers need to be able to respect constraints on arrival times of reaching a goal state imposed by the plan, as well as reaching that goal state itself.

This investigation addresses this challenge by modeling robotic systems as hybrid discrete/continuous systems rather than just discrete systems. This model-based approach features two key innovations. First, we have developed a representation for temporally and spatially flexible tasks for hybrid systems, called a *Qualitative State Plan* (QSP). A QSP consists of a sequence of qualitative states, which correspond to discrete operating modes of the hybrid system. Each qualitative state has an associated set of continuous dynamic characteristics, and a set of temporal and spatial goals represented as constraints. We use the QSP representation to elevate the level of command of hybrid systems to the task level, while allowing the controller full latitude in responding to disturbances safely. Second, we have developed a *Model-based Executive* that executes QSPs. The Model-based Executive generates control actions that achieve the QSP goals, even if (bounded) disturbances occur. Key features of this executive are: 1) a whole-body controller that provides an abstraction of the hybrid system that is easier to control; 2) a plan compiler that transforms the QSP into an easily executable form called a *Qualitative Control Plan* (QCP), and 3) a plan dispatcher that executes the QCP. The whole-body controller transforms the robot, a system with tightly-coupled nonlinear dynamics, into a set of loosely-coupled linear systems [4]. This allows us to extend temporally flexible plan execution techniques, previously used only for discrete systems, to hybrid systems. The plan compiler incorporates compilation techniques used for temporally flexible plans, but extends these using recently developed algorithms for state reachability analysis and optimal controller synthesis. Thus, the plan compiler produces a QCP that contains feasible state and control input trajectory sets for the linearized abstraction. We call these trajectory sets *flow tubes*. The flow tube representation prunes infeasible trajectories from consideration at runtime, allowing the dispatcher to focus only on control actions that are feasible. Similarly, the QCP's compiled representations of qualitative state transition events, represented as a *dispatchable graph*, allows the dispatcher to focus only on control actions that correspond to feasible durations between events. Our dispatchable graph is similar to ones used previously for temporally flexible plan execution systems for discrete

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