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# Fluent Calculus Planning with Continuous Change

## Summary of the article

A new, expressive version of the Fluent Calculus has recently been developed around the concept of so-called state update axioms. We extend this formalism to reasoning about actions and planning in hybrid domains, which involve both discrete and continuous change.

The first step towards this end is to introduce fluents (i.e., atomic components of descriptions of world states) which are hybrid by themselves. Generally, a fluent is assumed to be stable in between the occurrence of two consecutive actions, and yet a fluent may internally represent a continuous process. Examples of such 'process fluents' can be: constant movement, acceleration, oscillation, dilatation and contraction, etc. Although it describes a particular continuous change, a hybrid fluent itself remains unchanged unless some action causes a discontinuity. World states in hybrid systems can thus be modeled as collections of both ordinary fluents and process fluents, which may be initiated and terminated by actions.

In a world full of ongoing processes, however, an agent executing a plan is not the only source of discontinuities. Also the laws of physics frequently imply state transitions. If, for instance, two moving objects eventually meet, then an 'autonomous' update of the system state happens, which can be viewed as the consequence of a so-called *natural* action. Based on the concept of successor state axioms as a solution to the Frame Problem in the Situation Calculus, Green's classical definition of planning by deduction has recently been generalized to domains with natural actions and continuous change. Reiter has shown that natural actions can be specified just like deliberative actions by preconditions and effects. A plan in his approach is defined as a sequence of action performances, a so-called situation term, of the form $Do(a_n, \ldots, Do(a_1, S_0)\ldots)$, starting in some initial situation $S_0$ and involving both deliberative actions by the agent and all natural actions that happen along the way.

However, we show that this approach is unsuited for planning under incomplete information. In a nutshell, the problem is that incomplete information may cause uncertainty about whether some natural action will happen or not. A planning problem may then admit no provably correct solution even if a simple sequence of deliberative actions will achieve the goal in any case.

Coming from this insight, we develop a theory of Fluent Calculus planning with continuous change based on the novel concept of a *situation tree with trajectories*: The natural actions are uncoupled from the situation term. A plan thus becomes what it used to be in the classical definition,

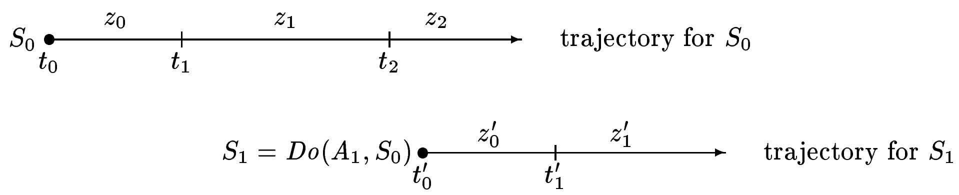


Figure 1: Each situation has its own trajectory, which describes how the state evolves according to the expected natural actions. For instance, in the example shown here, at the time $t'_0$ when the deliberative action $A_1$ is performed in situation $S_0$, the world is no longer in the initial state $z_0$ due to a natural action happening at time $t_1 < t'_0$. The effect of $A_1$ is to transform state $z_1$ into $z'_0$, which thus becomes the initial state of the trajectory for situation $Doy(A_1, S_0)$.

namely, a sequence of deliberative actions to be performed by the planning agent. An implication of this view is that natural actions cause state transitions without effecting a new situation. To this end, each situation has a *trajectory*. A trajectory is a sequence of states. The world starts in a particular state whenever a new situation arises. This state shall be the first one on the situation's trajectory, and the further evolution of the trajectory is then determined by the natural actions that are expected to happen. The performance of a deliberative action, on the other hand, brings about a new situation with its own trajectory; see Fig. 1.

In this way we obtain a better generalization of the classical definition of planning by deduction, which is applicable to planning problems with incomplete knowledge of world states. Incidentally, the crucial step of introducing situation trees with trajectories also enables solutions to Zeno's paradox: This more theoretical problem arises whenever an infinite series of natural actions happen in a finite interval. In our theory, no restrictions are imposed regarding the number of states on a trajectory. We show how axioms on limits can thus be used to add to a trajectory the limit of an infinite sequence of states. This enables conclusions about the evolution of the world state beyond the boundaries of a finite interval which includes infinitely many natural actions.