Optimal Manufacturing Controller Synthesis Using Situation Calculus

Omar Adalat Daniele Scrimieri Savas Konur
University of Bradford, UK

Introduction

- **Controller synthesis in manufacturing systems** has the goal of synthesizing a *process controller* using:
  - a high-level target **process recipe**
  - lower-level behaviour formalised of **production resources** (robots, tools, sensors/probes, and machinery).
- **Situation Calculus**: a many-sorted second order logic for reasoning about actions with dynamic predicates, objects, and actions. All changes to the world are a result of named actions, with specified action preconditions and effect axioms. Facility actions are *compound*, with each production resource taking an atomic action (which may include no-operation/idling). Compound actions can have different rules applied contrasted to individually performing the constituent actions.

  ConGolog: a high-level *programming language* for the situation calculus, which allows introducing *non-determinism* & *true concurrency* (parallelism).
  Characteristic graphs: allow modelling ConGolog program execution states and transitions in a succinct manner (actions + conditions + variables).
- **Production resources** (robots and all equipment) are modelled with logical action theories + high-level ConGolog programs. Actions involve idling, preparatory actions (e.g. equipping bits, synchronized transferring parts between resources) and manufacturing operations (e.g. drilling a part, gluing parts, etc).
- **Process recipes** are modelled simply with a high-level ConGolog program, that only addresses high-level manufacturing behaviours (completely resource-agnostic, ignoring lower-level operations such as part transfers).

Objectives of controller synthesis

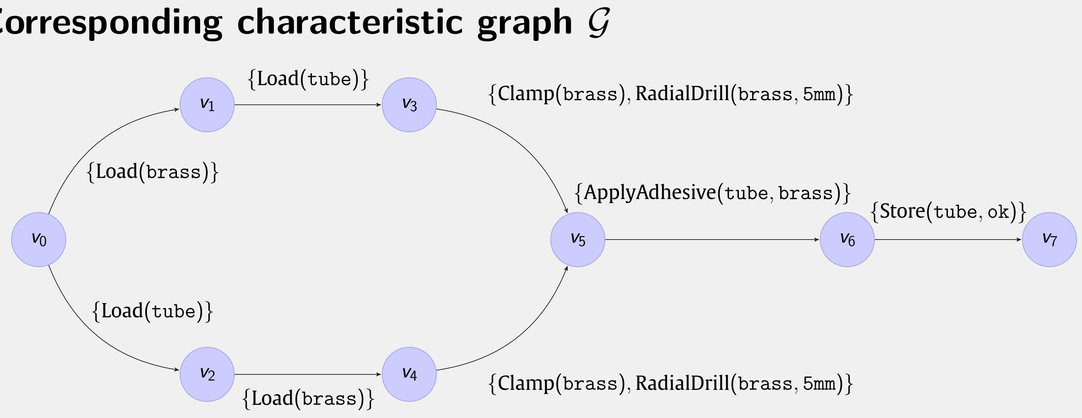
- **Finding optimal controllers** i.e. a controller which minimises the number of true concurrent and individual actions, or cost ascribed therewith.
- **Minimizing execution time of synthesis** our methods involve progression (forward search) which are amenable to heuristics.

Illustrative process recipe

ConGolog recipe program

$$\begin{gathered}\text{Load}(\texttt{brass}) \;||\; \text{Load}(\texttt{tube});\\ \text{Clamp}(\texttt{brass}) \;|||\; \text{RadialDrill}(\texttt{brass}, 5);\\ \text{ApplyAdhesive}(\texttt{tube}, \texttt{brass});\; \text{Store}(\texttt{brass}, \texttt{ok})\end{gathered}$$

Corresponding characteristic graph $\mathcal{G}$



Description

- In an interleaved fashion, load a brass part and a tube part. This can be done simultaneously, or potentially either after the other (weak concurrency).
- The brass part must be clamped and drilled - simultaneously/joint execution (true concurrency).
- Then, in sequence, apply adhesive and store the product with code ok.

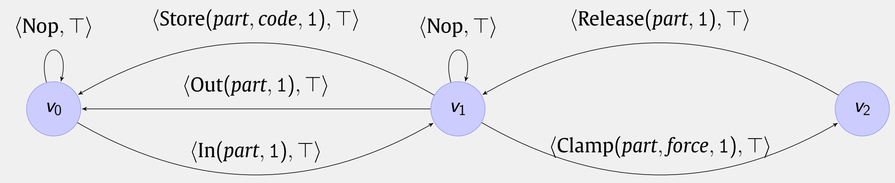
Illustrative production resource

A production resource's ConGolog program

loop:

$$\begin{gathered}\text{Nop}^* \mid (\text{In}(\textit{part}, 1); (\text{Nop} \mid (\text{Clamp}(\textit{part}, \textit{force}, 1); \text{Release}(\textit{part}, 1)))^*;\\ (\text{Out}(\textit{part}, 1) \mid \text{Store}(\textit{part}, \textit{code}, 1))\end{gathered}$$

Corresponding characteristic graph $\mathcal{G}$



Logical basic action theory $\mathcal{D}$

$$\begin{gathered}\text{Poss}(\text{Load}(\textit{part}, i, s) \equiv \textit{Part}(\textit{part}, s) \wedge \textit{on\_site}(\textit{part}, s)\\ \textit{on\_site}(\textit{part}, \text{do}(\mathbf{a}, s)) \equiv \textit{on\_site}(\textit{part}, s) \wedge \neg\exists\, i.\ \text{Load}(\textit{part}, i) \in \mathbf{a} \wedge \neg\exists\, \textit{code}, i.\ \text{Store}(\textit{part}, \textit{code}, i) \in \mathbf{a}\\ \textit{part}(\textit{part}, \text{do}(\mathbf{a}, s)) \equiv \textit{part}(\textit{part}, s) \wedge \neg\exists\, \textit{code}, i.\ \text{Store}(\textit{part}, \textit{code}, i) \in \mathbf{a} \wedge \exists\, \textit{other}, i.\ \text{ApplyAdhesive}(\textit{other}, \textit{part}, i) \in \mathbf{a}\end{gathered}$$

where Poss represents a precondition axiom and the other two formulae represent successor state axioms (changes the fluent's truth valuation based on the performed action from the binary function do).

Description

- The *loop*: construct means we are dealing with an **infinite** execution flow.
- The resource may indefinitely idle from the Nop* construct - another source of infinite execution.
- It may also take a *part* in from another resource, then potentially indefinitely follow an execution sequence of Nop or clamping with a particular force and a successive release in the next timestep. Proceeding this, it may transfer the *part* out to another resource, or it may store the *part* with a particular *code*.

Synthesis strategy & Future work

- We use a **progression** based search (forward search), imposing that all potential recipes are finite processes. We use a *fairness* assumption for strong cyclical planning, enforcing limits on infinite executions of resources.
- Heuristics can be used in a progression-based search by ascribing costs to atomic & compound actions and checking progress completion of controller candidates, for example A* and Greedy Best First Search.

Future work

- Can we **improve** non-optimal plans to optimality?
- Enhanced representations: **non-Markovian actions**, **explicit time**, **noisy and fallible sensing**, etc.

References

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- Sardina, S. and De Giacomo, G., 2009, June. *Composition of ConGolog programs*. In Twenty-First International Joint Conference on Artificial Intelligence.

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