Optimization-based control for dual-arm manipulation

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Background: Why constraint-based programming?

Problem:

Candidate solution: Trajectory planning

- Pan & brush trajectories $e(t)$
- Joint trajectories $q(t)$
Background: Why constraint-based programming?

Problem:

Candidate solution: Trajectory planning

- Pan&brush trajectories $e(t)$
- Joint trajectories $q(t)$

Drawbacks:

- Not reactive
- Hard to extend
Background: Why constraint-based programming?

Problem:

Candidate solution: Trajectory planing

- Pan&brush trajectories $e(t)$
- Joint trajectories $q(t)$

Drawbacks:

- Not reactive
- Hard to extend

Alternative:

- Constraint-based programming
How to use constraint-based programming?

Example:

- Specifying constraints:
- Combining constraints.

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How to use constraint-based programming?

Example:

- Specifying constraints:
  - Relative position
  - Brush orientation
  - Contact force
  - Obstacle avoidance
  - Singularity avoidance

- Combining constraints.
Build a monster from something simple
Build a monster from something simple
Seminal earlier works in constraint-based programming

- Additional tasks (Seraji 1989)
- User defined objective functions (Peng and Adachi 1993)
- Stack of Tasks (Mansard and Chaumette 2007)
- iTaSC (De Schutter 2007)
- Sub-tasks (Tatlicioglu 2008)
- Prioritizing linear equality and inequality systems (Kanoun 2009)
Dual arm manipulation using constraint based programming
Contributions

Our formulation of constraint-based programming

Quadratic optimization problem:

- 2014 IFAC:
  Dual arm manipulation using constraint-based programming.
- 2012 Syroco:
  A multi objective control approach to online dual arm manipulation.
Our formulation of constraint-based programming

Quadratic optimization problem:

\[
\min_u \quad \dot{f}_j(q(t), u, t) + u^T Qu, \quad j \in I
\]

\(Q\) is a diagonal positive definite matrix.
Our formulation of constraint-based programming

Quadratic optimization problem:

\[
\begin{align*}
\min_u & \quad \hat{f}_j(q(t), u, t) + u^T Qu, \quad j \in l \\
\text{(s.t.)} & \quad \hat{f}_m(q, u, t) \leq b_m, \quad \forall m \in l_{ie},
\end{align*}
\]

where \( b_m, b_n \) are positive scalars and \( Q \) is a diagonal positive definite matrix.
Our formulation of constraint-based programming

Quadratic optimization problem:

\[
\begin{align*}
\min_u & \quad \dot{f}_j(q(t), u, t) + u^T Qu, \quad j \in I \\
\text{(s.t.)} & \quad \dot{f}_m(q, u, t) \leq b_m, \quad \forall m \in I_{ie}, \\
& \quad \dot{f}_n(q, u, t) = b_n, \quad \forall n \in I_e,
\end{align*}
\]

where \(b_m, b_n\) are positive scalars and \(Q\) is a diagonal positive definite matrix.
Explicitly parameterize the convergence of each constraint:

\[
\begin{align*}
\dot{f}_m(q, t) & \leq b_m, \quad \forall m \in l_{ie}, \\
\dot{f}_n(q, t) & = b_n, \quad \forall n \in l_e,
\end{align*}
\]
Explicitly parameterize the convergence of each constraint:

\[ \dot{f}_m(q, t) \leq -k_m e_m, \quad \forall m \in I_{ie}, \]
\[ \dot{f}_n(q, t) = -k_n e_n, \quad \forall n \in I_e, \]
Explicitly parameterize the convergence of each constraint:

\[ \dot{f}_m(q, t) \leq -k_m(f_m(q, t) - b_m), \quad \forall m \in I_{ie}, \]
\[ \dot{f}_n(q, t) = -k_n(f_n(q, t) - b_n), \quad \forall n \in I_e, \]
Time-forward terms:

$$
\dot{f}_m(q, t) \leq -k_m(f_m(q, t) - b_m), \quad \forall m \in I_{ie},
$$

$$
\dot{f}_n(q, t) = -k_n(f_n(q, t) - b_n), \quad \forall n \in I_e,
$$
Time-forward terms:

\[
\frac{\partial f_m(q, t)}{\partial q} \dot{q} \leq -k_m (f_m(q, t) - b_m) - \frac{\partial f_m(q, t)}{\partial t}, \quad \forall m \in I_{ie},
\]

\[
\frac{\partial f_n(q, t)}{\partial q} \dot{q} = -k_n (f_n(q, t) - b_n) - \frac{\partial f_n(q, t)}{\partial t}, \quad \forall n \in I_e,
\]
Prioritizing the constraints:

\[
\min_{\mathbf{u}} \quad \dot{f}_j(\mathbf{q}(t), \mathbf{u}, t) + \mathbf{u}^T \mathbf{Q} \mathbf{u}, \quad j \in I
\]

(s.t.)

\[
\dot{f}_m(\mathbf{q}, \mathbf{u}, t) \leq -k_m(f_m(\mathbf{q}, t) - b_m), \quad \forall m \in l_{ie},
\]

\[
\dot{f}_n(\mathbf{q}, \mathbf{u}, t) = -k_n(f_n(\mathbf{q}, t) - b_n), \quad \forall n \in l_e,
\]

where \(k_m, b_m\) are positive scalars and \(\mathbf{Q}\) is a diagonal positive definite matrix.
Prioritizing the constraints:

\[
\begin{align*}
\min_u & \quad \dot{f}_j(q(t), u, t) + u^T Qu + \mu^T W \mu, \quad j \in I \\
(\text{s.t.}) & \quad \dot{f}_m(q, u, t) + \mu_m \leq -k_m(f_m(q, t) - b_m), \quad \forall m \in I_{ie}, \\
& \quad \dot{f}_n(q, u, t) + \mu_n = -k_n(f_n(q, t) - b_n), \quad \forall n \in I_e,
\end{align*}
\]

where \(k_m, b_m\) are positive scalars and \(Q, W\) are diagonal positive definite matrices.
Our formulation of constraint-based programming

Advantages:

- Compact formulation of a QP including equalities and inequalities.
- Time feed-forward terms.
- Parameterize the convergence rate.
Circular trajectory in the pan cleaning task

Different convergence rate in simulation:
Circular trajectory in the pan cleaning task

Experiment on a dual-arm robot:
Circular trajectory in the pan cleaning task

Experiment with contact force control:

Tool relative to frying pan

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Performance indices

Contributions

Validation through examples

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Human robot co-manipulation

Dual arm manipulation with close-chain constraints

Human robot co-manipulation
Future work

Human robot co-manipulation
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- EU FP7 project RoboHow.Cog
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Questions?