Stability-based motion planning of a tracked mobile manipulator over rough terrains

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Context

Maintenance, decommissioning or rescue interventions in Nuclear Facilities require:

1. to build maps of the environment
2. to explore constrained and/or unstructured areas for diagnosis purposes
3. to manipulate objects and physically interact with the environment

...in (semi-)autonomous or tele-operated ways.

(1) and (3) will be discussed by my colleague Philippe Bidaud this afternoon.

In this talk we focus on (2).
Motivation

Planning and controlling the motion of mobile robots for safely traversing uneven terrains are not simple tasks.

In the present work...

Assuming the manipulator’s mass is non-negligible with respect to the robot-base’s mass,

what? increase the mobile manipulator’s stability for traversing uneven terrains,

how? by exploiting the manipulator’s DoFs.
Context of the present work: FRAUDO* project

FRAUDO*: FRanchissement AUtomatique D’Obstacles

Develop a robust and efficient robotic system that offers the possibility to autonomously navigate over uneven terrains which suppose great difficulties for even experienced human operators when such a robotic system is teleoperated.

Approach

- Perception
- 3D Mapping
- Localization
- Motion estimation
- Motion planning and control

Kinect
3D RGB Images
Linear Accelerations
Angular velocities
IMU
Cameleon
Odometry
Control input

ROS Architecture

Start / Stop
6D pose
Goal
3D map

Supervision
Execution control

Eca Robotics

Operator

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**Past work: BiDDTRRT algorithm**

| Terrain  | Algorithm | Iterations [-] | # Nodes [-] | Time [s] | Path length [m] | $\mathcal{J} = (1 - \hat{\xi})$ [-] | Success rate [%]|% |
|----------|-----------|----------------|-------------|----------|-----------------|-----------------|----------------|
| Terrain I | BiRRT     | 67352.106      | 291.847     | 2.500    | 4.361           | 1.801           | 95.0           |
|          | BiTRRT    | 107083.180     | 346.281     | 4.443    | 4.264           | 1.782           | 99.0           |
|          | BiDDTRRT  | 19336.600      | 132.000     | 1.852    | 4.290           | 1.031           | 100.0          |
| Terrain II| BiRRT     | 5214.678       | 444.356     | 0.545    | 17.689          | 6.311           | 100.0          |
|          | BiTRRT    | 16929.478      | 1293.067    | 2.104    | 19.042          | 3.360           | 100.0          |
|          | BiDDTRRT  | 10809.400      | 1887.400    | 4.813    | 18.091          | 2.506           | 100.0          |
| Terrain III| BiRRT    | 339.522        | 311.989     | 0.335    | 9.981           | 34.752          | 100.0          |
|          | BiTRRT    | 1387.611       | 328.867     | 0.929    | 12.732          | 2.610           | 100.0          |
|          | BiDDTRRT  | 1326.400       | 242.000     | 2.209    | 12.250          | 0.907           | 100.0          |
| Terrain IV | BiRRT    | 7875.644       | 1214.611    | 1.193    | 15.042          | 31.674          | 100.0          |
|          | BiTRRT    | 103657.221     | 1389.426    | 15.704   | 15.054          | 26.152          | 78.0           |
|          | BiDDTRRT  | 8821.800       | 373.400     | 5.683    | 14.023          | 13.329          | 100.0          |

\[a\] The success rate is defined as the ratio of the number of trials in which a solution is found within $L=10^6$ iterations to the total number of trials.
Corridor + stairs

Real "sensor-based" 3D map + stairs

Flippers contribution to traction capabilities

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Problem statement / Goal

Given a trajectory for the robot base

1. To generate trajectory for the arm’s center of mass for improving the robot’s overall stability
2. To track this trajectory using an Inverse-Velocity Kinematics-based controller

Possible applications

This approach may contribute in:

1. Finding stability-augmented paths
2. Even enlarging the solution-feasibility region
Key task in the stability-based planning

Given a configuration of the robot base,

search for the stability-optimal location of the arm’s center of mass
**Tip-over stability** (force-angle stability measure)

1. \[ \mu = \min_j (\theta_j) \| f_r \|, \quad j = \{1, \cdots, n\} \]
2. \[ f_r = f_g \] (quasi-static approach)
3. \[ \theta_j = \sigma_j \cos^{-1} \left( f_r^T \Phi_j^T \Phi_j \left( p_{j+1} - \xi_0 \right) \right) \]
4. \[ \bar{\xi}_O = \frac{m_A \bar{\xi}_A + m_B \bar{\xi}_B}{m_T} \]

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\[ \sigma_j = \begin{cases} 1, & \left( \Phi_j f_r \times \hat{i}_j \right)^T \hat{a}_j > 0 \\ -1, & \text{otherwise.} \end{cases} \]

\[ \Phi_j = (I - \hat{a}_j \hat{a}_j^T) \]

\[ \hat{a}_j = a_j / \| a_j \| \]

\[ \hat{i}_j = l_j / \| l_j \| \]

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**2D case**
Search for the stability-optimal location of the arm’s CoM

Set of valid and non-valid locations

Set of non-valid locations

Set of valid locations
Covariance Matrix Adaptation

1. Update the mean of the distribution of successful candidate solutions
2. Update the covariance matrix of the distribution such that the likelihood of previous search steps is increased

\[
f(x,y) = 0.1 \cdot (-x^2 - y^2)
\]

\[
\max_{\xi_A} \mathcal{F} \left( \bar{\xi}_A \right) \\
\text{s.t. } \bar{\xi}_A \in S_V \\
\mathcal{F}(t) = \omega_1 \frac{\mu}{\mu_{\text{max}}} - \omega_2 \frac{\left( \bar{\xi}_{A}^{(t)} - \bar{\xi}_{A}^{(t-1)} \right)^2}{d_{\text{workspace}}^2}
\]
Planning results

\[
\max_{\bar{\xi}_A} \quad \mathcal{F}(\bar{\xi}_A)
\]

\[
s.t. \quad \bar{\xi}_A \in S_V
\]

\[
\mathcal{F}(t) = \omega_1 \frac{\mu}{\mu_{\text{max}}} - \omega_2 \frac{\left(\bar{\xi}_A^{(t)} - \bar{\xi}_A^{(t-1)}\right)^2}{d_{\text{workspace}}^2}
\]
Inverse-velocity kinematics-based trajectory tracking

\[
\min_{\dot{q}} \quad \frac{1}{2} \left\| G \ddot{\xi} - G \dot{\xi} (\dot{q}) \right\|_{\omega_\xi}^2 + \frac{1}{2} (\ddot{\gamma} - \dot{\gamma} (\dot{q}))^2_{\omega_\gamma} + \frac{\varepsilon}{2} \left\| \dot{q} \right\|_{\omega_q}^2,
\]

s.t.

\[
q \leq q_{\text{limit}},
\]

\[
\dot{q} \leq \dot{q}_{\text{limit}},
\]

\[
v^T G R_B J_c \dot{q} \geq \frac{\varepsilon_d - d_k}{n \Delta t}.
\]

where

\[
d^{(k+1)} = d^{(k)} + v^T \dot{A}_c \Delta t \geq \varepsilon_d
\]

\[
\dot{A}_c = G R_B J_{A_c} \dot{q}
\]

\[
G \ddot{\xi} = \begin{bmatrix} G \ddot{\xi}_A, G \ddot{\xi}_B \end{bmatrix}^T \quad G \dot{\xi} = \begin{bmatrix} G \dot{\xi}_A, G \dot{\xi}_B \end{bmatrix}^T
\]

\[
G \ddot{\xi}_A \triangleq [\dddot{X}_A, \dddot{Y}_A, \dddot{Z}_A]^T \quad G \dot{\xi}_A \triangleq [X_A, Y_A, Z_A]^T
\]

\[
G \ddot{\xi}_B \triangleq [\dddot{X}_B, \dddot{Y}_B, \dddot{Z}_B]^T \quad G \dot{\xi}_B \triangleq [X_B, Y_B, Z_B]^T
\]

Video
Trajectory tracking performance

- Arm tracking error in the task space
- Base tracking error in the task space
- Arm joint angular velocities
- Base joint angular velocities
- Stability

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Summary

- Mobile manipulator navigation in unstructured environment
- RRT-type planning algorithm used to find feasible paths on uneven terrains
- Stability-optimal location of the arm’s CoM searched at each node using an efficient, locally optimal algorithm: Covariance Matrix Adaptation
- Reactive trajectory tracking achieved using a constraint-compliant IVK controller
- Improved stability and terrain crossing capabilities

Perspectives

- Real platform implementation
- The tracking may not go well and replanning online is very costly
- Reactively adapt the arm COM in order to maximize the stability measure for the current state, instead of the planned one
Thank you for your attention