Workspace Optimization
for Autonomous Mobile Manipulation

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Many tasks related to robotic space intervention, such as satellite servicing, require the ability of acting in an unstructured environment through autonomous mobile manipulation.

When introducing levels of autonomy in robotic intervention, several issues appear repeatedly.

The full cycle of an autonomous intervention is here presented through a case study in underwater robotics, a project called the Semi-Autonomous Underwater Vehicle for Intervention Missions\(^1\).

\(^1\)SAUVIM began in 1997 at the University of Hawaii at Manoa, under Prof. Junku Yuh. The project was funded by the Office of Naval Research over a 10 year period and administered by Dr. J. Yuh, S.K Choi and G. Marani.
Introduction
Autonomous Mobile Manipulation

➤ **Issue 1: Target area navigation.**
One of the most important aspects in autonomy is the environment perception. The best solution is determined by several factors, including task and environment.
Introduction

Autonomous Mobile Manipulation

► **Issue 2: Vehicle positioning.** An autonomous servicer must be capable of performing workspace optimization, correcting the vehicle position for maximizing the manipulability of the arm during its operations.
Issue 3: Arm control system. Cope with many issues commonly seen in robotics (kinematic singularities, collisions, joint limit, motor saturation, etc).
An autonomous robotic system must be able to intelligently cope all the above situations to successfully complete the given mission, whenever possible.
Kinematic control

Autonomous manipulation system:

- performs intervention tasks with limited human supervision;
- the human operator should be able to control the manipulation process with only high-level commands;
- the robot determines what joint trajectories need to be followed for successfully achieving goals.
Resolved Motion Rate Control (RMRC) is a local method for solving inverse kinematics problems. Given a generic task \( r = f(q) \), it uses the Jacobian \( J \) of the forward kinematics to describe a change in the end-effector position:

\[
\delta r = \frac{\partial f}{\partial q} \delta q = J(q) \delta q
\]

(1)

In RMRC we compute \( \delta q \) for a given \( \delta r \) and \( q \) by solving the above linear system. The solution, in the general form, is\(^2\):

\[
\delta q = J^+(q) \delta r + (I_n - J^+(q) J(q)) y
\]

(2)

where \( J^+(q) \) is the Moore-Penrose pseudo-inverse of \( J(q) \), \( y \) is an arbitrary vector and \( I_n \) indicates an identity matrix.

\(^2\)Y. Nakamura: Advanced Robotics: Redundancy and Optimization, Addison Wesley, 1991
Nakamura introduced the inverse kinematics taking into account of the priority of the subtasks:

\[
\delta q = J_1^+ \delta r_1 + \hat{J}_2^+ (\delta r_2 - J_2 J_1^+ \delta_r) , \quad \hat{J}_2 = J_2 (I_n - J_1^+ J_1)
\]
Example with:

- Task 1 (higher priority): Cartesian position of the end-effector
- Task 2 (lower priority): orientation of the end-effector
The direct implementation of the task priority in its original form

\[ \delta q = J_1^+ \delta r_1 + \hat{J}_2^+ (\delta r_2 - J_2 J_1^+ \delta r_1) \]  (3)

presents difficulties due to physical and mathematical singularities:

- **Kinematic singularities**: loss of rank of \( J_1 \) and \( J_2 \).
- **Algorithmic singularities**: loss of rank of \( \hat{J}_2 \) with \( J_1 \) and \( J_2 \) of full rank
To solve the previous problem we use the concept of **Task reconstruction**.
The basic idea in task reconstruction is to circumscribe singularities by moving, when approaching to them, on a hyper-surfaces where the distance index (*measure of manipulability*) remains constants.

**Figure: Conceptual diagram of Task Reconstruction**
Task reconstruction process

- **Phase 1**: definition of a distance index

In case of singualities avoidance, the "distance from singularities" index is given by the measure of manipulability (MOM), introduced by Yoshikawa:

\[
\mu(J) = \sqrt{\det(JJ^T)}.
\] (4)

\(\mu(J)\) takes a continuous non-negative scalar value and becomes equal to zero only when the Jacobian matrix is not full rank.
Task reconstruction process

- **Phase 2: application**

\[
\delta q = J^+ (q) \ TR (J, m(q), \delta r)
\]

where:

\[
TR (J, m(q), \delta r) = (I_m - k_1 n_m n_m^T) \delta r + k_2 n_m
\]

\[
n_m = \left( \frac{\partial m(q)}{\partial q} J^+ \right)^T \frac{\| \partial m(q) J^+ \|}{\| \partial m(q) J^+ \|}
\]

\[
k_1 = \frac{1 - \text{sign}(\delta r \cdot n_m)}{2} k_m (m, \bar{m}, \bar{m})
\]

\[
k_2 = K_r k_m \left( m, \frac{\bar{m}}{2}, \frac{\bar{m}}{2} \right)
\]

\[^3\text{Marani, G, Yuh, J., Introduction to Autonomous Manipulation, Springer Tracts in Advanced Robotics}\]
Task reconstruction process

Figure: Geometric interpretation of the task reconstruction concept
Task reconstruction example

- Cartesian position has priority over orientation
Kinematic control
Task Reconstruction

TR advantages:

▶ Fewer tuning parameters (mainly the distance limit)
▶ The performance is then simply affected by the choice of the lower limit.
▶ Based on a real-time evaluation of the measure of manipulability, this method does not require a preliminary knowledge of the singular configurations
▶ Can be regarded as a dynamic priority-changing algorithm.
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With a different choice of the distance index, the TR algorithm can be applied also to:

- collision avoidance
- joint limits avoidance
- workspace optimization
Collision avoidance

▷ **Index**: "minimum distance between all objects"

Task Reconstruction: application to self collision avoidance

Semi-Autonomous Underwater Vehicle for Intervention Missions

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Joint limits avoidance. Index:

\[ P(q) \equiv \prod_{i=1}^{n} N_p(q_i), \quad N_p(q_i) = 1 - \left( \frac{2(q_i - q_{i,\min})}{(q_{i,\max} - q_{i,\min}) - 1} \right)^2 \]

Example with imposed joint limits \((0, \pi/2)\) to elbow and wrist:
The whole vehicle-navigation system is regarded as unique open chain with multi-degrees of freedom joint

- joint 1 is a 6 DOF joint
- joints 2 through 8 are 1 DOF rotational
**Goal:**
- target optimally positioned within the dexterous arm workspace.

**Implementation:**
- **TR index**: measure of manipulability of the whole chain
- **Task** $r_1$ (3 DOF): Cartesian position of Link 8 (the end-effector)
- **Task** $r_2$ (3 DOF): Orientation of Link 8 (the end-effector)
- **Task** $r_3$ (3 DOF): Position ($x$ and $y$) and orientation (around $z$) of the vehicle (hovering condition)

\[\text{In our implementation, the hovering condition is achieved by setting to zero the time derivative of the third manipulation variable.}\]
Result

- The vehicle position is autonomously changed only when needed, to increase the manipulability of the arm:
Workspace optimization
Experimental results with SAUVIM

Measure of manipulability of $J_1$ (linear)

![Graph showing the measure of manipulability of $J_1$ over time.](image-url)
Workspace optimization
Experimental results with SAUVIM

Measure of manipulability of $J_2$ (angular)

![Graph showing manipulability over time](chart.png)
Conclusions

- Robotic systems capable of operating autonomously in unstructured environments will need this type of complete solution strategy.
- Many issues appear repeatedly in autonomous robotic manipulation (of all areas):
  - target area navigation
  - vehicle positioning
  - arm control systems

Giacomo Marani, Junku Yuh: 
*Introduction to Autonomous Manipulation*
Springer Tracts in Advanced Robotics
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