REACTIVE MOTION PLANNING FOR MOBILE CONTINUUM ARM IN DYNAMIC INDUSTRIAL ENVIRONMENT

The 19th International Conference on Climbing and Walking Robots and Support Technologies for Mobile Machines
Industrial Manipulators

RIGID-LINK MANIPULATORS

PRECISE POSITION CONTROL

WIDELY USED

WORKS SEPARATELY FROM HUMAN DUE TO SAFETY REASON

MANIPULATION ONLY VIA END EFFECTOR

IN GENERAL NEED OPEN SPACE
Continuum Manipulators

**HIGHER FLEXIBILITY**
Able to bend at any point
Possess inherent compliance

**IMPROVED DEXTERITY**
Able to perform whole-arm manipulation

**WIDER APPLICATION**
Able to manoeuvre in tight space
Applied for surgical application
Promising candidate for industrial manipulation

McMahan, et al, ICRA 2006
Continuum Manipulators

COMPLEX MODELLING
Highly-flexible structure
Complex dynamic

DIFFICULT TO CONTROL
Nonlinearity

DIFFICULT TO ESTIMATE THE POSE

LACKS AUTONOMY
Research on going
Assume static and well-defined environment
Lacks constraint avoidance

Xiao, et al, IROS 2010
Torres, et al, IROS 2011
Tendon-Driven Continuum Manipulator

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Obstacle and Constraint Avoidance
Modified Potential Field: Obstacle Avoidance

**ATTRACT END EFFECTOR TO GOAL**

**REPEL OBSTACLE FROM ROBOT’S BODY**

**POTENTIAL FIELD AS A VELOCITY TASK-SPACE**

**INVERSE JACOBIAN PRODUCING FIELD IN ACTUATOR SPACE**

Attractive field: \( \dot{x}_{at} = -\nabla U_{at}(x) = -k(x - x_d) \)

Repulsive field: \( \dot{x}_{rep}(x) = -\nabla U_{rep}(x) = \begin{cases} \eta \left( \frac{1}{\rho_b} - \frac{1}{\rho_0} \right) \frac{1}{\rho_b^2} \frac{\partial \Phi_b}{\partial x} & \text{if } \rho_b < \rho_0 \\ 0 & \text{if } \rho_b > \rho_0 \end{cases} \)
Modified Potential Field: Constraint Avoidance

**TENDON’S LENGTH LIMIT:** \((1 - \xi)L < l_{ij} < (1 + \xi)L\)

**APPLIED IN ACTUATOR SPACE:**

\[
\dot{q}_{lim}(q) = -2\sigma \frac{1}{\xi^2L^2}(1 - L),
\]

**ATTRACT TENDON TO NORMAL LENGTH**

**DEPEND ALSO ON THE DISTANCE BETWEEN TIP AND TARGET:**

- **Weight function** depend on **tip-to-target-distance**:
  \[
  w(x) = (1 - e^{-\mu \|x-x_d\|})
  \]
- The proposed **mechanical constraint avoidance**:
  \[
  \dot{q}_{new}(q,x) = \begin{bmatrix} 0_{6\times1} \\ w(x)\dot{q}_{lim}(q) \end{bmatrix}
  \]
Simulation Results
Simulation Results

With Constraint Avoidance

Without Constraint Avoidance
Experimental Results

- Tip’s trajectory
- Target trajectory
- Tip-obstacle distance
- Target-obstacle distance
Pose Estimation and Safer Obstacle Avoidance for Continuum Manipulator
State-Space Representation for Pose Estimation

TENDON'S LENGTH AS A STATE:
\[
\mathbf{x} = \mathbf{q} = \begin{bmatrix} q_1 & q_2 & \ldots & q_n \end{bmatrix}^T
\]

THE RATE OF TENDON’S LENGTH AS AN INPUT:
\[
\mathbf{u} = \mathbf{q} = \begin{bmatrix} q_1 & q_2 & \ldots & q_n \end{bmatrix}^T
\]

STATE EQUATION:
\[
\mathbf{x}_{k+1} = f(\mathbf{x}_k, \mathbf{u}_k) = \mathbf{x}_k + \Delta t \mathbf{u}_k,
\]

OUTPUT EQUATION:
\[
\mathbf{y}_k = g(\mathbf{x}_k) = \begin{bmatrix} p(\mathbf{x}_k, \xi = \chi_1) & \ldots & p(\mathbf{x}_k, \xi = \chi_n) \end{bmatrix}^T
\]
Local Observability Analysis for Single-segment

Linearized Model:
\[
A_k = \frac{\partial f(x_k, u_k)}{\partial x_k} = I \in \mathbb{R}^{3 \times 3},
\]
\[
C_k = \frac{\partial g(x_k)}{\partial x_k} = \frac{\partial p(q_k, \xi = 1)}{\partial q_k} = J(q_k, \xi = 1).
\]

Jacobian:
\[
J(q, \xi) = \frac{\partial p(k, \xi)}{\partial k} \frac{\partial k}{\partial q} = J_k J_q,
\]
\[
J_q = \begin{bmatrix}
\frac{3(l_1 l_2 + l_4 l_3 - l_2^2 - l_3^2)}{d l_1^2 l_4} & \frac{3(l_1 l_2 - l_2 l_3 l_4)}{d l_2^2 l_4} & \frac{3(l_1 - l_3 l_2 - l_2 l_3 + l_3^2)}{d l_2^2 l_4}
\end{bmatrix},
\]
\[
J_k = \begin{bmatrix}
\cos \phi (k \sin \kappa + \cos \kappa - 1) & - \frac{\sin \phi (1 - \cos \kappa)}{\kappa} & \frac{\cos \phi \sin \kappa}{\kappa} \\
\sin \phi (k \sin \kappa + \cos \kappa - 1) & \frac{\cos \phi (1 - \cos \kappa)}{\kappa} & - \frac{\sin \phi \sin \kappa}{\kappa} \\
k \cos \kappa \sin \kappa & \frac{\cos \phi \sin \kappa}{\kappa} & \cos \kappa \sin \kappa
\end{bmatrix},
\]
\[
l_+ = l_1 + l_2 + l_3, l_0 = \sqrt{l_1^2 + l_2^2 + l_3^2} - l_1 l_2 - l_1 l_3 - l_2 l_3.
\]

Observability Matrix:
\[
O = \begin{bmatrix}
C & CA & \ldots & CA^{n-1}
\end{bmatrix}^T
\]
\[
O = \begin{bmatrix}
J(q_k, \xi = 1) & J(q_k, \xi = 1) & J(q_k, \xi = 1)
\end{bmatrix}^T
\]

Observable Condition: 
\[
\text{rank}(O) = n = 3,
\]
\[
\text{rank}(O) = \text{rank}(J(q, \xi)).
\]

Proposition 1. The linearized system of the non-linear model described in (4.8)-(4.9) is observable at all state except the singular state. \( l_1 = l_2 = l_3 \) and \( \kappa = 0 \).
Pose Estimation for Single-Segment

Measurement: Position Sensor (Magnetic-Based Tracker) at the Tip

EKF produces the state estimation

The state estimation used to estimate the pose of the whole body and PSP:

$$\hat{p}_k(\xi) = p(\hat{x}_{k|k}; \xi).$$
Simulation Results

Zero Input Scenario
Tendon’s Length Estimation

Tip Pose Estimation

Sinusoidal Input Scenario
Tendon’s Length Estimation

Tip Pose Estimation
Simulation Results

Obstacle Close to Middle Part of Segment

Obstacle Close to the Tip
IMPLEMENTING STANDARD EKF HAS PROBLEM

- Possible to arrive at *physically impossible state*, such as *negative length*

MULTI-STAGE EKF:

- Implement EKF *gradually* from the bottom segment to the distal one
- EKF is used for *n* number of *active segment*
- A number of *active segment* *n* is incremented after the *tip’s position error* of the *previous segment* is lower than a value
**Pose Estimation for Multi-Segment**

**Combining Pose Estimation and Obstacle Avoidance:**

- Combining pose estimation and obstacle avoidance from the beginning → **incorrect pose estimation & incorrect movement**.
- Necessary to **deactivate the obstacle avoidance stage at the beginning of estimation process**
- Activate it when the sum of the **tip position estimation errors** for all segments is less than a predefined threshold
Simulation Results – Zero Input

Multi-Stages EKF

Tendon’s Length Estimation

Pose Estimation

Standard EKF

Tendon’s Length Estimation

Pose Estimation

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Simulation Results – Sinusoidal Input

Tendon’s Length Estimation

Pose Estimation

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Simulation Results

Obstacle Close to Bottom Segment

Obstacle Close to Middle Segment
Possible Application to Industrial Setting
THE PRECISE POSITION CONTROL OF RIGID-LINK MANIPULATOR

FLEXIBILITY AND DEXTERITY OF CONTINUUM MANIPULATOR
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