Kinematics, position and force control issue in minimally invasive surgery

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Introduction

Minimally invasive surgery (MIS)

- Long instruments
- Small incisions
- Endoscope for visual feedback
Drawbacks or difficulties in MIS

- Penetration point accessibility, loss of degree of freedom or mobility, reduced orientation capabilities and limited amplitude of motions

- Hand-eye coordination (reverse hand motion, scaling of motion,…)

- Loss of natural haptic feedback increased difficulty for knots, force sensing, lead traction,…

- Reduced point of view
The surgeon manipulates instruments through a master device. The instruments are moved by robotized manipulator.
Open problems

- Kinematics (guaranteeing trocar constraint, redundancy, …)
- Distal mobilities for increasing manipulability or dexterity inside patient
- Technology (mechanism, actuator, sensor, space occupancy, …)
- Control architecture (accuracy, force feedback, correct hand–eye coordination, scaling position and/or force, …)
- Gesture assistance functions (physiological motion compensation, automatic camera guidance, …)
- Safety
Introduction

**General objective:** Design **kinematics** and synthesize a **control architecture** providing **force feedback** and **augmented vision** of the operating site to the surgeon by means of a **teleoperated** master slave system with **high dexterity**.
Contents

❌ Kinematics and motion control

  • Carrier

    • **Constrained kinematics** / spherical wrist
      • Position control (geometric control approaches, dynamic decoupling control,…)
      • Force control

  • High dexterity instrument

❌ Interaction control

❌ Teleoperated systems
Arms with kinematics constraint
- The idea is to create a mechanical structure able to give the tool one SPECIFIC type of motion
- Mostly applied to mini-invasive surgery

M.I.S. a tool (shape ⇔ cylinder) passes through a trocar (shape ⇔ ⊗ annulus)

The tool axis always passes in one “fixed” point

Two constraints (translation is constrained in two directions)
Gruebler formula: Mobility = (Total dof) – (6 x Nb of loops)

How many dof for respecting the constraints?

Mobility \rightarrow Tx, Ty, Tz \rightarrow 3

3 = (4 + ?) – (6 x 1)
\Rightarrow ? = 5

Mobility \rightarrow Tx, Ty, Tz, Rz \rightarrow 4

4 = (4 + ?) – (6 x 1)
\Rightarrow ? = 6
Well known slave kinematics to mechanically create a fixed point that coincides with the penetration point.

- Passive universal joint (Zeus)
- Remote center device (da Vinci, Artemis…)}
Option 1: passive joints

- Mobility $\rightarrow$ Tx, Ty, Tz $\rightarrow$ 3
- $3 = (4 + 5) - (6 \times 1)$

Zeus

- 5 joints
- -
- 3 motors
- 2 passive joints

P    R    R    R    R
Option 2: Remote Center of Motion

A classical spherical wrist does not rotate at the “right” point.

A RCM system does and thus “cancel” the constraint.
RCM or “The Magical Parallelogram”

- RCM with spherical links requires complex parts but can be more compact
  (See examples later)

- … while a basic parallelogram may do the job as well
RCM in motion

Da Vinci
RCM: other solutions…

From solid links to timing belts

ARTEMIS - FZK
Summary of solutions with kinematics constraint

Option 1 (passive joints)
- Few motors
- The trocar “forces” the passive joint to adapt “mechanically”
- No accurate positioning is needed
- Safety at the expense of motion accuracy and stiffness

Option 2 (active RCM)
- Few joints and motors
- The trocar has no influence on the arm motion
- BUT, the arm MUST be precisely located (positioning device + procedure)

Spherical wrist
Kinematics and motion control

• Carrier
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  • Force control

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Interaction control

Teleoperated systems
Small occupancy robotics mechanisms for endoscopic surgery [Nakamura 2002]

Problem: « the occupation of the space in operating room! It sometimes prohibits surgeons from accessing patients in an emergency. Surgical robot systems should be small. »

Active trocar:

2-dof rotation
1-dof translation

Weight: 1kg including the drive part
Spherical wrist and portable solutions…

- Spherical optimized mechanism [Hannaford 04] wrt workspace requirements for MIS and practical joint limits

Blue DRAGON: system for measuring the position and orientation of two endoscopic tools along with the forces and torques applied to the tools in a minimally invasive environment [Hannaford 02].
Generic surgical tasks: tissue handling/examination, tissue dissection and suturing.

Analysis performed on an animal model in-vivo by 30 surgeons: 95% of the time the surgical tools positions encompass a 60º cone.

Reachable workspace of an endoscopic tool performed on a human model: to reach the full extent of the abdomen the tool needed to be moved 90º in the lateral/medial direction (left to right) and 60º in the superior/inferior (foot to head) direction.

⚠️ Design space optimization wrt mechanism isotropy
LER Light Endoscopic Robot [Berkelman 03] [TIMC, Grenoble, France]

Mass:
LER 625 g
Endoscope and Camera 300-500 g typical

Backdriveability:
Torque 0.45 N.m
Backdrive force on fully extended endosc. 1.5 N
Dimensions: height 75 mm, diameter 110 mm

Motion range: azimuth rotation 360° continuous, inclination to 80° from vertical, extension 160 mm

Max. speed: azimuth rot. 20 deg.s⁻¹, inclination 20 deg.s⁻¹, extension 25 mm.s⁻¹

Max. torque limit: 6 N.m

Max. force on fully extended endoscope: 20 N

Voice control
Spherical wrist and portable solutions…

MC²E [LRP, Paris, France]

- **Lower part:**
  - spherical 2-dof mechanism ($\Theta_1$ and $\Theta_2$)
  - intersecting axes realize fulcrum point
- **Upper part:** mounted on trocar ($\Theta_3$ and $d_4$)
- **Currently 4-dof at distal end**
The bone-mounted miniature MARS robot [Shoham 2003]

- precise position and orientation of long, handheld surgical instruments, such as a drill or a needle, with respect to a surgical target
- small work volume enclosing a sphere whose radius is several centimeters
- lightweight and compact structure
- lockable structure at given configurations to provide rigid guidance
- capable of withstanding lateral forces resulting from instrument guidance of up to 10 N
- repeatedly sterilizable in its entirety or easily covered with a sterile sleeve
- quick and easy installation and removal from the bone.
Option 3 (spherical wrist)

- The wrist may require complex parts
- But it can be easily located on the trocar
- However it is still rather cumbersome on the patient if the surgeon has to locate 3 of them

Position control + versatile carrier
Contents

▷ Kinematics and motion control

• Carrier

  • Constrained kinematics / spherical wrist
  • **Position control** (geometrical control approaches, dynamic decoupling control,…)
  • Force control

• High dexterity instrument

▷ Interaction control

▷ Teleoperated systems
Option 3 : position control

Geometric constraints satisfaction of the penetration point solved by an optimization procedure [Michelin 04a]
Option 3 : position control

1st approach: kinematic dependant [Michelin 04a]

For a desired tool position, the elbow and wrist positions are computed by solving geometrical constraints ensuring the penetration point position.
Option 3: position control

2nd approach: kinematic independent [Michelin 04a]

Description of the constraint in terms of virtual mechanical joint
Background: Khatib’s work on redundant robots [Khatib 87]

\[ \Gamma = \Gamma_{\text{task}} + \Gamma_{\text{posture}} \]

\[ \Gamma_{\text{task}} = J^T F \]  
External F force acting on the robot

\[ \Gamma_{\text{posture}} = (I_n - J^T J^+ T)\Gamma_{\text{null}} \]

\[ \Gamma_{\text{null}} : \text{arbitrary null space control torque which can be arbitrarily chosen} \]
**Optimization:** $\Gamma_{\text{null}}$ is used to force to zero the distance between the instrument and the trocar or to minimize the contact force applied to the trocar

$$\Gamma_{\text{null}} = \alpha \nabla \phi \quad \Rightarrow \quad \Gamma = J^T F + (I_N - J^T J^+) \alpha \nabla \phi$$

**Dynamic decoupling control scheme:**
Experimental results

The algorithm has been implemented on an experimental platform D2M2:

- A 5-dof slave arm teleoperated by a master arm (Phantom 1.5) through Ethernet link and UDP protocol
- Equipped with direct drives actuators ➔ high dynamics, low friction
- F/T sensor fixed at the extremity of the carrier (between carrier and instrument)

Tested trajectories: straight line, circular and helicoidal paths

Sample rate: 0.7 ms
Computing time: 0.35 ms
Experimental results
Perspective: Control of tree redundant structures

Generic algorithm that makes it useable for controlling high dexterity redundant instrument
Kinematics and motion control

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  • **Force control**
  • High dexterity instrument

Interaction control

Teleoperated systems
Option 4: force control

- Mobility $\Rightarrow$ Tx, Ty, Tz $\Rightarrow$ 3
- $3 = (4 + 5) - (6 \times 1)$

5 joints & 5 motors

2 dof can be controlled with force measurements

(See details in the lecture of G. Morel)
A summary of solutions ...

- Option 1 (passive joints)
  - Few motors
  - The trocar “forces” the passive joint to adapt “mechanically”
  - No accurate positioning is needed

- Option 2 (active RCM)
  - Few joints and motors
  - The trocar has no influence on the arm motion
  - BUT, the arm MUST be precisely located (positioning device + procedure)

- Option 3 (spherical wrist)
  - The wrist may require complex parts
  - But it can be easily located on the trocar
  - However it is still rather cumbersome on the patient if the surgeon has to locate 3 of them
A summary of solutions ...

- Option 4 (position control)
  - Versatile robot
  - No accurate positioning

- Option 5 (force control)
  - The trocar "forces" the joint to adapt by means of measures + control software
  - A bit more complex

These two options may open a path to "multi-purpose" systems
Contents

 caractère

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 Teleoperated systems
Instrument with high dexterity

Sensorized and Actuated Instruments for Minimally Invasive Robotic Surgery [DLR, Munich, Germany]

- Full manipulability: universal joint with intersecting axes for twisting the gripper about its longitudinal axis without pivoting the instrument shaft about the point of insertion.

- Prototype diameter: 10 mm

- Range of motion: 40° in both directions.
Instrument with high dexterity

- Manipulation forces: 20 N at the instrument tip
  - Gripping force: 20 N.

- Gripper actuated by one cable counteracted by a spring.

- The cable force necessary to close the gripper and securely hold a needle: 70 N.

- Maximum driving forces for the joint actuation: 100 N.

- To guarantee zero backlash, the cables are prestressed with the maximal expected driving force, accounting for a worst case cable force of 200 N.
Miniaturized Force/Torque Sensor

- 6-dof hexapod (high stiffness, adaptable properties, annular shape, scalability) with flexural joints
- Diameter: 10 mm
- Strain gauge sensor
- Forces: +/- 30 N
- Torques: +/- 300 Nmm
Instrument with high dexterity

Modular mechanical design:
- External Ø = 10 mm ; length = 24 mm (1 dof) and 36 mm (2 dof)
- Usefull stroke = ± 90° et > 360° (roll)
- Torque = 6 mN.m et 8 mN.m (roll)
- Brushless micro-actuators Ø 3 mm
- Magnetic resolver -> angular position
Proposed solution:

- 4 modules: 1-dof / 2-dof / 2-dof / Gripper
- Total Length = 11 cm
- On going manufacturing of the 1st prototype
- Module 1-dof: Ø = 1 cm, L = 3,6 cm
Instrument with high dexterity
Instrument with high dexterity

Hyper redundant miniature manipulator « hyper finger » for remote MIS in deep area [Ikuta 03]
Instrument with high dexterity

- Micro-robot MIPS with 3-dof for endoscopy (2000) [Merlet 00, INRIA Sophia, France]

Diameter 8.6mm, length 2.5cm
Half way to go …

Motion control

- Carrier
  - Constrained kinematics / spherical wrist
  - Position control (geometrical control approaches, dynamic decoupling control, predictive control,…)
  - Force control

- High dexterity instrument

Interaction control

Teleoperated systems


RCM: other “unique” solutions...