Preoperative Planning for the Multi-arm Surgical Robot using PSO-GP-based Performance Optimization

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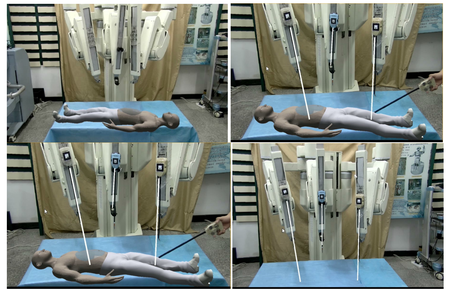
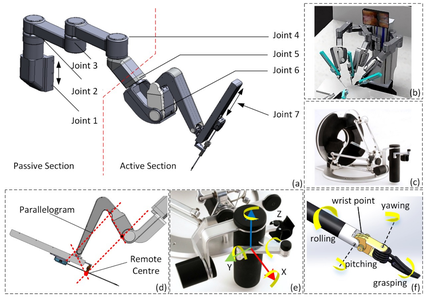
RESEARCH GOAL

The Bigger target is to let the *multi-arm* surgical robot achieve *optimal performance* during surgery

- Hand-held Devices
- Motion Planning of the surgical robot
- Preoperative Planning
- Augmented Reality
- And so on





- Three robotic arms
  endoscope arm
  instrument arm
- Passive joints
  Joint 1, 2, 3, 4, adjusted manually before the operation
- Active joints
  Joint 5, 6, 7, controlled by the surgeon through the master haptic device during surgery
- Remote Centre of Motion (RCM)
- Instrument
  four DOFs: pitching, yawing, rolling, grasping
- Haptic device Omega.7

Contribution

- Robot learning by imitation
- Viewpoint invariant human action recognition by 3D skeleton
- Affordance based articulated object/tool categorisation & manipulation
- Motion retargeting to robots

PREVIOUS APPROACHES

- Port locations and robot positioning are given by surgeons.
- One robotic arm

> ***multi-arm* surgical robot performance metrics**

CONTACT

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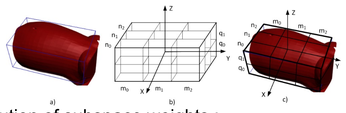
METHODOLOGY

Workspace subdivision

- Simplify the surgical workspace as a hexahedron
- Divide the surgical workspace into several subspaces
- Size of each subspace: $(7-10)\text{cm} \times (7-10)\text{cm} \times (7-10)\text{cm}$



Distribution of subspace weights :

- Not designed randomly.
- Distribution of hotspots of the surgical workspace, which is derived from the Computed Tomography (CT) scan data.

Global Isotropy Index (GII)

Jacobian matrix + Workspace Subdivision Subspace Weight

- ❑ A *global measure* of isotropy that indicates how accurately and consistently *a robot arm* behaves throughout the entire surgical workspace.
- ❑ Describing both the reachability and the isotropy of the robotic arm in the surgical workspace.

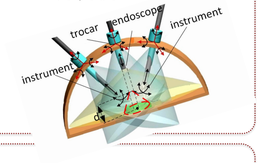
$$GII = \sum_{i=0}^{M-1}\sum_{j=0}^{N-1}\sum_{k=0}^{Q-1} \omega_{ijk}\gamma_{ijk} \frac{\min\limits_{\boldsymbol{a}_0 \in S_{ijk}} \sigma_{min}(\boldsymbol{J}(\boldsymbol{a}_0))}{\max\limits_{\boldsymbol{a}_1 \in S_{ijk}} \sigma_{max}(\boldsymbol{J}(\boldsymbol{a}_1))}$$

L. Stocco, S. Salcudean, and F. Sassani, *"Fast constrained global minimax optimization of robot parameters,"* *Robotica*, vol. 16, no. 06, pp. 595–605, 1998.

Cooperation Capability Index (CCI)

- ❑ Cooperation Point:
  - Reachability: the point which both the end-effectors of the two instrument arms can reach
  - Visibility: the point on the axis of the endoscope arm; acceptable vision distance
- ❑ Cooperation Workspace
  - The region that consists of all Cooperation Points
- ❑ A global measure that evaluates the performance of *the multi-arm cooperation* throughout the entire surgical workspace.

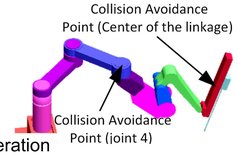
$$CCI = \sum_{i=0}^{M-1}\sum_{j=0}^{N-1}\sum_{k=0}^{Q-1} \omega_{ijk}\frac{V_e \cap V_{t1} \cap V_{t2}}{V_{S_{ijk}}}$$



Minimum Distance Index (MDI)

- ❑ MDI calculates the minimum sum of the distances between the selected collision avoidance points at three robotic arms in the Cooperation Workspace.
- ❑ Collision avoidance points: Joint 4; the center of the last linkage

$$MDI = \min\Big(\sum_{i=1}^{k}\sum_{j=1}^{k}|\boldsymbol{P}(t1,i)-\boldsymbol{P}(e,j)|^2 + \sum_{i=1}^{k}\sum_{j=1}^{k}|\boldsymbol{P}(e,i)-\boldsymbol{P}(t2,j)|^2\Big)$$



- ❑ Minimal Distance Maximization: the minimal distance (MDI) in the Cooperation Workspace should be maximized to *decrease the possibility of collision*.

Optimization

- constrained optimisation problem
- Algorithm: Particle Swarm Optimization, Gaussian Process

$$(\boldsymbol{P}_4^*, \boldsymbol{\theta}_4^*) = \underset{\boldsymbol{P}_4, \boldsymbol{\theta}_4}{\operatorname{argmax}}\, L(\boldsymbol{P}_4, \boldsymbol{\theta}_4)$$

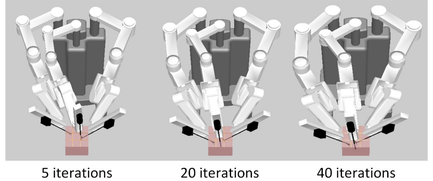
$$L(\boldsymbol{P}_4, \boldsymbol{\theta}_4) = \omega_1(GII_{t1} + GII_{t2} + GII_e) + \omega_2 CCI + \omega_3 MDI$$

EXPERIMENTAL RESULTS

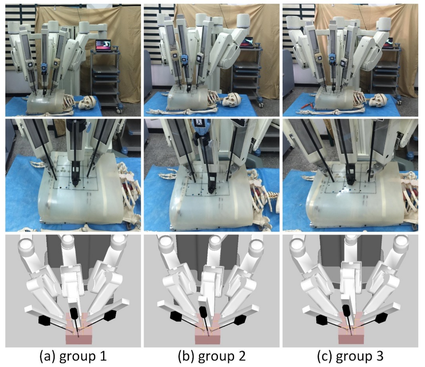
Setup

- surgical workspace: 250mm × 250mm × 150mm hexahedron
- workspace subdivision: 3(M) × 3(N) × 2(Q) subspaces
- layer q_1: space for the trocar, insufflation with gas (pneumoperitoneum), weights are assigned as 0
- four groups of experiments with different subspace weight distributions

✓ Online Optimization Evaluation

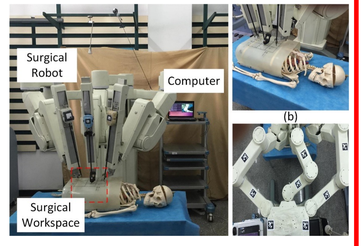


5 iterations 20 iterations 40 iterations



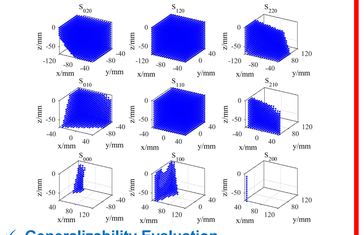
(a) group 1 (b) group 2 (c) group 3

✓ Verify the effectiveness of the optimization results

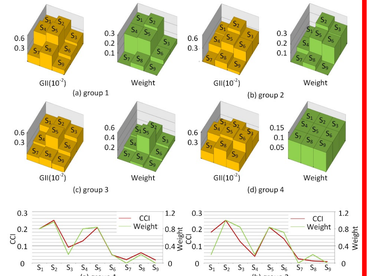


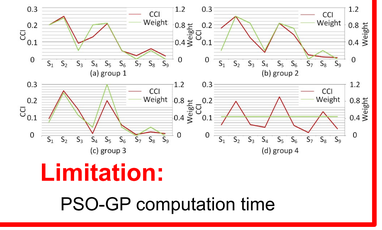
group	Subspaces weights in layer q_0				
	S_{020}	S_{120}	S_{220}	S_{010}	S_{110}
1	0.20	0.24	0.05	0.19	0.22
2	0.05	0.26	0.20	0.05	0.20
3	0.07	0.25	0.13	0.05	0.40

group	Subspaces weights in layer q_0				layer q_1
	S_{210}	S_{000}	S_{110}	S_{220}	
1	0.05	0.00	0.05	0.00	0.00
2	0.19	0.00	0.05	0.00	0.00
3	0.05	0.00	0.05	0.00	0.00



✓ Generalizability Evaluation





Limitation:

PSO-GP computation time