Project number: _T42-409/18-R_

RESEARCH GRANTS COUNCIL
THEME-BASED RESEARCH SCHEME (TRS)

Completion Report on Funded Project

Project start date: *1 December 2018*
Project completion date: *30 November 2023*

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1. Project Title: Image-guided Automatic Robotic Surgery

2. Names and Academic Affiliations of Project Team Members#

Project team member	Name / Post	Unit / Department / Institution	Average number of hours per week spent on this project in the whole project period
Project Coordinator (PC)	Liu Yunhui / Choh-Ming Li Professor and Director	T Stone Robotics Institute / CUHK	25
Co-Principal Investigator(s)	Sung Joseph Jao Yiu* / Dean and Distinguished University Professor	Lee Kong Chian School of Medicine/Nanyang Technological University, Singapore (wef 1 Apr 2021)	10
	Meng Max Qing Hu* / Chair Professor	Electronic and Electrical Eng. /Southern University of Science and Technology (.wef 9 Jan 2023)	10
	Chiu Philip Wai Yan / Professor	Surgery/CUHK	10
	Huang Jie# / Choh-Ming Li Professor	Mech. & Automat. Eng. /CUHK	10

	FENG Gary Gang# / Chair Professor	Biomedical Eng. /CityU (.wef 23 Dec 2022)	10
	Kwok Ka Wai / Assistant Professor	Mechanical Eng. /HKU	10
	Tong Michael Chi Fai / Professor and Chairman	Otorhinolaryngology, Head and Neck Surgery/CUHK	10
	Au Samuel Kwok Wai / Associate Professor	Mech. & Automat. Eng. /CUHK	10
	Liao Wei Hsin / Choh-Ming Li Professor	Mech. & Automat. Eng. /CUHK (.wef 1 Sep 2024)	10
	Yam Yeung / Research Professor	Mech. & Automat. Eng. /CUHK	10
	Heng Pheng Ann / Professor	Computer Science &Eng. /CUHK	10
	Cheung Tak Hong / Consultant	Gynaecology/Prince of Wales Hospital	10
Co-Investigator(s)	Li Xiang* / Associate Professor	Automation / Tsinghua University (wef 22 Aug 2019)	15
	Chan Jason Ying Kuen / Assistant Professor	Otorhinolaryngology, Head and Neck Surgery/CUHK	10
	Wang Zerui* / Co-founder	Cornerstone Robotics Limited (wef 21 October 2019)	30
	Greiffenhagen Christian* / Associate Professor	Sociology /PolyU	10
Collaborators	Taylor Russell H. / Professor	Computer Sci. /Johns Hopkins University	N.A.
	Yang Guangzhong* / Founding Dean	Institute of Medical Robotics / Shanghai Jiao Tong University (wef 1 Oct 2019)	N.A.
	Sorger Jonathan / Vice President	Medical Research / Intuitive Surgical	N.A.
	Nelson Bradly / Professor	Mech. & Process Eng. /ETH Zürich	N.A.
	Fiorini Paolo / Professor	Computer Science/ University of Verona	N.A.

*Original affiliation of the below members:

SUNG Joseph Jao Yiu: Mok Hing Yiu Professor, Department of Medicine & Therapeutics/CUHK

MENG Max Qing Hu: Professor, Department of Electronic Engineering/CUHK

LI Xiang: Research Assistant Professor, Department of Mechanical and Automation Eng., CUHK

WANG Zerui: Research Assistant Professor, Department of Mechanical and Automation Eng., CUHK

Greiffenhagen Christia: Assistant Professor, Department of Sociology, CUHK

YANG Guangzhong: Professor and Director, Hamlyn Centre, Imperial College of London

\# *Please highlight the approved changes in the project team composition and quote the date when the RGC granted approval of such changes. For changes in the project team composition, please submit a separate request, together with the justification and the curriculum vitae of the new member(s), to the RGC three months prior to the intended effective date of the change.*

3. Project Objectives

Summary of objectives addressed/achieved:

Objectives*	Percentage achieved	Remarks**
Real-time sensing and perception: Stage 1: 1. Design the 3D imaging system; 2. Design the shape and force sensors using FBG; 3. Develop the model for tissue simulations; Stage 2: 1. Build the prototype of the 3D imaging system; 2. Develop the FBG-based sensors; 3. Develop the tissue parameters estimation algorithm. Stage 3: 1. Improve real-time efficiency of the 3D imaging system using GPU acceleration and implement the system; 2. Build and implement the FBG-based shape and force sensors for instruments; 3. Improve the robustness of the tissue parameter estimation algorithm to noises and disturbances. Stage 4: 1. Evaluate the 3D imaging system by experiments and improve its performance based on the experiments; 2. Evaluate the FBG-based sensors by experiments and improve the performance based	100%	

Objectives*	Percentage achieved	Remarks**
on the experiments; 3. Verify and improve the tissue parameter estimation algorithm by experiments. Stage 5: 1. Verify the performance of the 3D imaging system, the FBG-based sensors, and the model estimation algorithm by ex-vivo and clinical experiments.		
Image-guided surgery planning and navigation: Stage 1: 1. Design and build the surgical database; 2. Design the surgical simulation system; 3. Design the surgical navigation system; Stage 2: 1. Develop the algorithms for patient matching and preliminary plan generation; 2. Develop the algorithms for real-time visualization and simulation of surgical objects; 3. Develop the algorithms for image-based soft tissue registration and surgical navigation. Stage 3: 1. Build the virtual environment; 2. Develop the technology for local surgical planning; 3. Build the image-based navigation system. Stage 4:	100%	

Objectives*	Percentage achieved	Remarks**
1. Complete the data-driven surgical planning system; 2. Complete the surgical simulation environment; 3. Complete the image-based surgical navigation system. Stage 5: 1. Verify the performance of the surgical planning, simulation and navigation systems by ex-vivo and clinical experiments.		
Image-guided motion/action control: Stage 1: 1. Design and calculate the shape-descriptors of soft tissues; 2. Develop the controller for a single robot to perform surgical operations on soft tissues; 3. Develop the simulation environment for deformation control; Stage 2: 1. Investigate the stability and robustness of the controller; 2. Verify the performance by experiments; 3. Design the cooperation controller of multiple robots performing cooperative tasks such as suturing, etc. Stage 3: 1. Improve the deformation controller for a single robot; 2. Implement the cooperation controllers and verify its	100%	

Objectives*	Percentage achieved	Remarks**
performance by experiments; 3. Develop the surgeon-robot collaboration controllers. Stage 4: 1. Improve the performance of the deformation controller for a single robot; 2. Implement the cooperation controllers and verify its performance by experiments; 3. Develop the surgeon-robot collaboration controllers. Stage 5: 1. Verify the performance of the deformation controller, the cooperative controllers and the surgeon-robot collaboration controllers by ex-vivo and clinical experiments.		
Robotic surgery intelligence: Stage 1: 1. Develop an algorithm for recognizing surgical instruments and their actions using 2D videos; 2. Develop the algorithm for reconstructing 3D information of surgical filed from the 2D videos obtained by the da Vinci robot; Stage 2: 1. Improve and verify the algorithm for recognizing surgical flow using 2D images/videos; 2. Design the deep learning network for recognizing surgical situations using both	100%	

Objectives*	Percentage achieved	Remarks**
2D and 3D images/videos. Stage 3: 1. Improve the deep learning network; 2. Train the deep learning network using huge database of 2D videos. Stage 4: 1. Implement the deep learning methods on the prototype systems; 2. Verify their performance by experiments. Stage 5: 1. Verify the performance of the developed surgical intelligence for recognising situations and surgical steps by ex-vivo and clinical experiments.		
System integration and case studies: Stage 1: 1. Develop the hardware and software environment for tracking and navigating surgical robots and surgeons in the operating room; 2. Design the interfaces for our surgical robot to manipulate the instruments made by Intuitive Surgical Inc; Stage 2: 1. Complete the hardware development of the navigation system; 2. Develop the interface for mounting sensors on the da Vinci Research Kit;	100%	

Objectives*	Percentage achieved	Remarks**
3. Develop the controller for controlling the Intuitive instruments from our robots. Stage 3: 1. Implement the sensing and control technologies on the da Vinci Research Kit; 2. Carry out experiments using the da Vinci Research Kit; 3. Implement the methods on the prototype built on our own robots. Stage 4: 1. Implement the surgical planning and intelligence technologies on the Da Vinci Research Kit; and carry out experimental verification; 2. Pass the required EMC tests of the prototype; 3. Carry our the ex-vivo experiments for Phase 1, Phase 2 and Phase 3 clinical experiments; 4. Apply for the approval of the clinical trials of Phase 1 and conduct the trials. Stage 5: 1. Apply for the approval and conduct the clinical trials of Phase 2; 2. Apply for the approval for clinical trials of Phase 3 and carry out the trails if approved.		

* *Please highlight the approved changes in objectives and quote the date when the RGC granted approval of such changes.*

** *Please provide reasons for significantly slower rate of progress than originally planned.*

6. Research Highlights and Outputs

6.1 What are the most exciting research accomplishments of the project?

(Please list five or more of the team's best research accomplishments, such as journal and conference papers, software codes, research infrastructure, etc. For each item, please clearly justify how it has achieved international excellence (e.g. best paper award, invited presentation, citations, product licensed to industry, etc.))

The Five Most Exciting Research Accomplishments

1. **Real-time sensing framework for surgical robots:** We developed cutting-edged real-time perception and sensing technologies in both hardware and software, with notable awards and high-impact publications. Our team has developed a 3D endoscopic imaging system capable of accurate and real-time 3D reconstruction in surgical scenes, achieving a speed of over 10 Hz and a reconstruction accuracy of less than 1 mm, which has been validated by third-party testing. The relevant works have been published in IROS, TASE, and TBME. Additionally, we advanced learning-based techniques for monocular depth estimation, 3D reconstruction, and rendering in surgical scenes, with publications in TASE, TBME, and MICCAI. Our pioneering work in deformable tissue reconstruction and rendering has been published in MICCAI 2022 with the oral presentation, student travel award, and young scientist award. Recently, our scale-aware monocular depth estimation method for endoscopic images was shortlisted for Best Paper at MICCAI 2024, demonstrating our contributions in improving precision and accuracy in surgical reconstruction.

2. **Novel algorithms for surgical planning/navigation:** We developed advanced data-driven approaches for surgical planning in several robotic systems, achieving notable accomplishments published in top robotics journals. For enhanced soft robot navigation under limited visual information, we fused optical camera input with sparse strain data from Fiber Bragg Gratings (FBGs). Additionally, we designed a hybrid controller combining kinematic and data-driven algorithms for obstacle-robust target tracking. This approach, coupled with online learning and SLAM, enabled training and refinement of an FBG-based pose estimator in a data-driven manner, published in IEEE Transactions on Robotics (TRO). In MRI-guided transoral laser microsurgery, we introduced a machine learning-based controller for precise visual servoing of laser spots along designated paths on the camera view. Using a neural network trained with 2D laser spot displacements, the model enabled real-time control (> 100 Hz) with a tracking error below 200 μm. This work, published in Science Robotics, won the HKU Research Output Prize, demonstrating cutting-edge accuracy in surgical automation.

3. **Novel algorithms for surgical robot control:** We designed novel image-guided control algorithms for the manipulation of soft surgical objects and the coordination of surgical robots. Innovative model-free controllers have been developed to handle surgical objects with varied properties, eliminating the need for complicated physical models. The controllers are general, capable of processing different visual measurements in diverse surgical environments, ensuring broad applicability. Additionally, the controllers demonstrate good real-time performance, facilitating quick responses during surgical operations. Furthermore, they are designed with guaranteed stabilities to ensure reliability and safety for surgical task execution. These research works lead to publications in top journals such as IEEE Transactions on Robotics (TRO) and the International Journal of Robotics Research (IJRR), and our team members have been invited to present these advancements at leading robotics conferences like ICRA and IROS.

4. **Advanced robotic surgical intelligence:** We propose a novel framework for automatic surgical gesture recognition, which is fundamentally important to enable intelligent cognitive assistance in robotic surgery. Our proposed framework, named MRG-Net, integrates multi-modal relational graph network to dynamically integrate visual and kinematics information to boost gesture recognition accuracies. This work is published in ICRA 2021 and received the Best Paper Award in Medical Robotics. In addition, we designed a simulation platform, named SurRoL, which is a reinforcement learning centered and dVRK compatible platform for surgical robot learning, and it is dedicated to surgical embodied intelligence with strong focus on learning algorithm support and extendable infrastructure design. The platform is open source and has been widely used by researchers at multiple research institutions and universities around the world. Related paper has been published at top conference and journal, such as ICRA, IROS, ISMR, RAL, et al.

5. **Advanced surgical robotic systems:** The integration of advanced robotics technology has led to the development of three significant surgical robotic systems aimed at enhancing computer-aided

interventions. First, a multi-port endoscopic surgical robot for minimally invasive surgery, developed with Cornerstone Robotics Limited, features a surgeon console and multi-arm manipulators and has successfully undergone multi-center clinical trials and received approval from the National Medical Products Administration (NMPA) for usage in Mainland and Hong Kong. Second, a flexible miniature surgical robot, commercialized through Agilis Robotics Limited, introduces thin, dexterous arms compatible with existing endoscopes, validated through animal studies. Lastly, an innovative one-surgeon-four-arm system, integrating image-based tracking, facilitates laparoscopic hysterectomy with enhanced precision and efficiency, validated through cadaver experiments. These systems, compliant with international safety standards, have undergone extensive case studies including ex-vivo, in-vivo, and clinical validations, showcasing promising results and paving the way for commercialization.

Details of the Research Accomplishments

Topic 1: Image-Based Sensing/Perception

1. 3D real-time imaging system

We proposed a 3D endoscopic imaging system that can realize dense 3D reconstruction in real time (Fig. 1). Based on the active stereo technique which yields high-density, accurate and robust 3D reconstruction by combining structured light and stereo vision, we design a endoscopic system consisting of two image feedback channels and one pattern projection channel. Remote high-speed image acquisition and pattern generation lay the foundation for the real-time dense 3D surface reconstruction and enable the miniaturization of the endoscopic probe. To enhance the reconstruction efficiency and accuracy, we propose a novel active stereo method by which the dense 3D point cloud is obtained using only five patterns, while most existing multiple-shot structured light techniques require 10–40 patterns. The established prototype system has shown good performance in reconstructing surface of biological tissues. Compared with the existing structured light techniques, the proposed method shows better real-time efficiency and accuracy in both quantitative and qualitative ways. Furthermore, our endoscopic system has passed the third-party test and verified the performance with reconstruction speed over 10 Hz, optical resolution over 20 lp/mm, and reconstruction accuracy less than 1mm (Fig. 2). Ex-vivo experiments demonstrate the robustness of the proposed method to different biological organs and the effectiveness to lesions and deformations of the organs. The related works have been published in IROS, TASE and TBME.

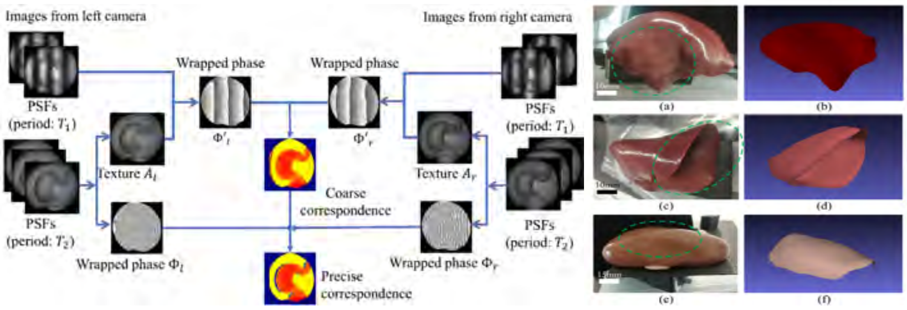

Fig. 1. The illustration of the proposed active stereo method and reconstruction results of a porcine liver

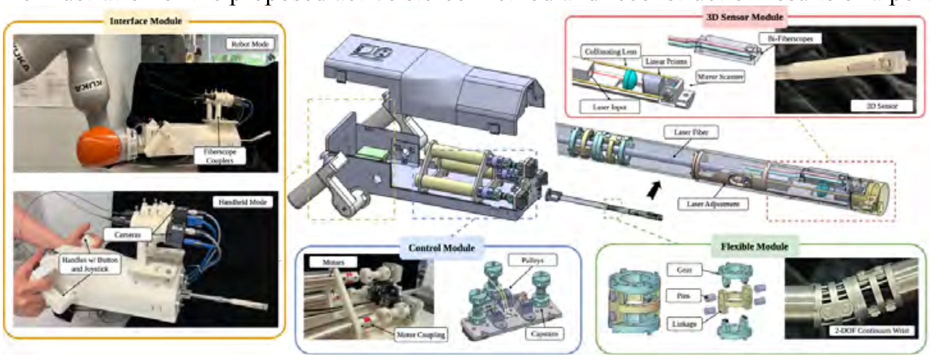

Fig. 2 The structure design of the designed 3D endoscopic imaging system

2. Monocular depth estimation

To realize the accurate estimation of absolute depth from a monocular endoscope, we have proposed a novel framework called SADER, which explores vision and robot kinematics to estimate the high-quality absolute depth for monocular surgical scenes. To jointly learn the multi-modal data, we introduce a self-distillation based two-stage training policy in the framework (Fig. 3). In the first stage, a boosting depth module based on vision transformer is proposed to improve the relative depth estimation network that is trained in a self-supervised method. Then, we develop an algorithm to automatically compute the scale from robot kinematics. By coupling the scale and relative depth data, pseudo absolute depth labels for all images are yielded. In the second stage, we re-train the network with 3D loss supervised by pseudo labels. Additionally, we did cadaver experiments to collect new surgical depth estimation data about robotic laparoscopy for evaluation. Experimental results on public SCARED and cadaver data demonstrate that the SADER outperforms previous state-of-art even stereo-based methods with an accuracy error under 1.90 mm, proving the feasibility of our approach to recover the absolute depth with monocular inputs (Fig. 4). The related papers of monocular depth estimation have been published in TASE, MICCAI.

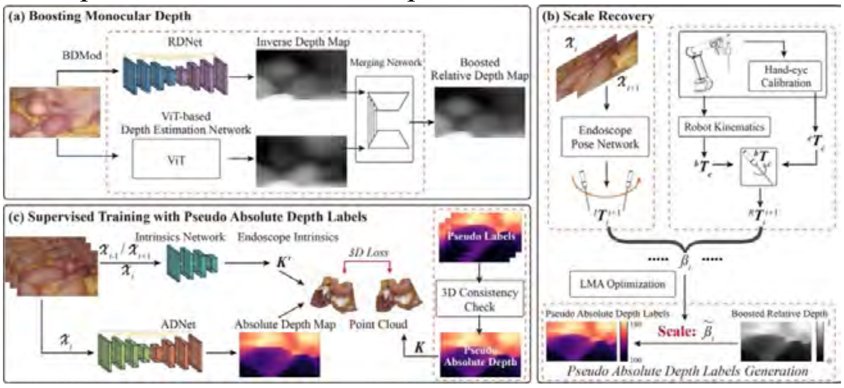

Fig. 3. Overview of the self-distillation based two-stage training policy.

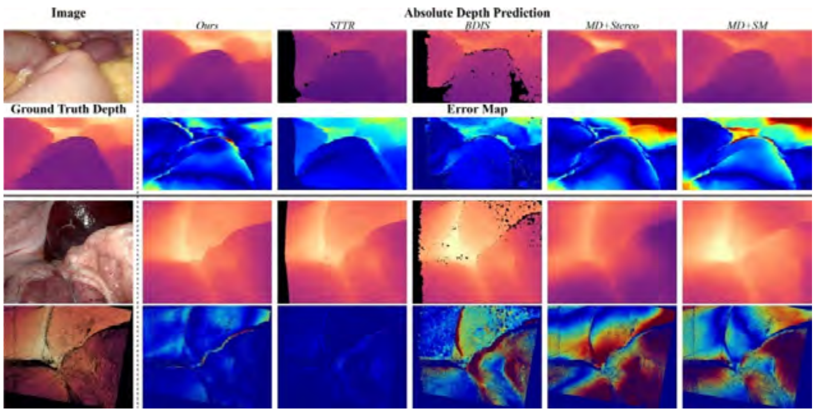

Fig. 4. Qualitative comparison of the absolute depth estimation on CADAVER and SCARED data.

3. 3D Reconstruction from Endoscopic Images

- Stereo reconstruction of deformable tissues:

Surgical scene reconstruction is a crucial task for many applications such as intra-operative navigation and image-guided robotic surgery automation. However, this is a challenging task in robotic minimally invasive surgery, due to the deformable tissues with significant topology changes. To address this challenge, we present a novel framework for deformable tissue reconstruction from binocular captures in robotics surgery under the single-viewpoint setting. As shown in Fig. 5, our framework adopts dynamic neural radiance fields to represent deformable surgical scenes in MLPs and optimize shapes and deformations in a learning-based manner. To address the particular tool occlusion problem in surgical scenes, we design a new mask-guided ray casting strategy for resolving tool occlusion. We incorporate a depth-cueing ray marching and depth-supervised optimization scheme, using stereo prior to enable neural implicit field reconstruction for single-viewpoint input. Compared with previous methods, our results exhibit great performance gain, both quantitatively and qualitatively, on 3D reconstruction and deformation tracking of surgical scenes (Fig. 6). The related paper of the deformable tissues reconstruction is published in MICCAI, with Student Travel Award, Young Scientist Award.

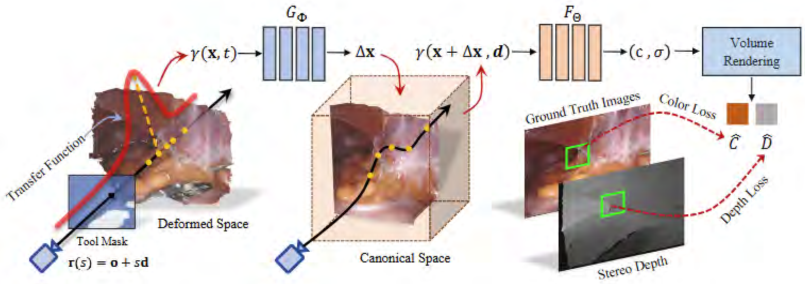

Fig. 5. Illustration of neural rendering for deformable tissue reconstruction

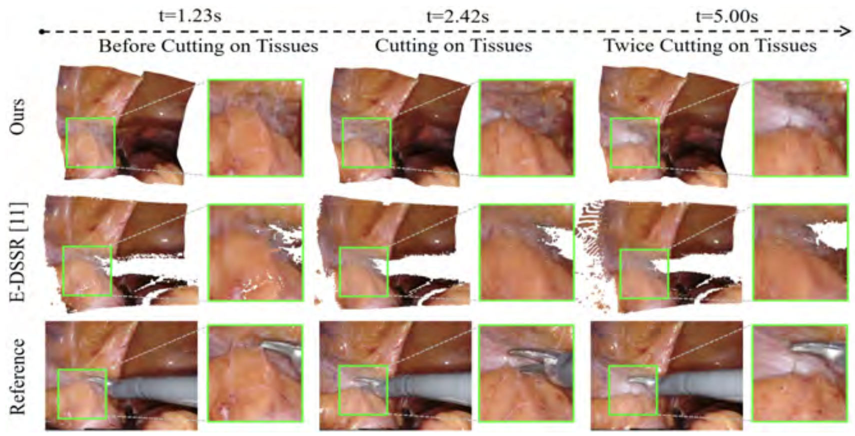

Fig. 6 Qualitative results of deformable tissue reconstruction

- 3D reconstruction and pose estimation from monocular image:

Reconstructing and localization from monocular images in surgical scenes plays a vital role in computer-assisted surgery. Recent advancements in 3D Gaussian Splatting (3DGS) have shown great potential for real-time novel view synthesis of general scenes. However, 3DGS with SfM fails to recover accurate camera poses and geometry in surgical scenes due to the challenges of minimal textures and photometric inconsistencies. To tackle this problem, we have proposed the first SfM-free 3DGS-based method for surgical scene reconstruction by jointly optimizing the camera poses and scene representation (Fig. 7). Based on the video continuity, the key of our method is to exploit the immediate optical flow priors to guide the projection flow derived from 3D Gaussians. Unlike most previous methods relying on photometric loss only, we formulate the pose estimation problem as minimizing the flow loss between the projection flow and optical flow. A consistency check is further introduced to filter the flow outliers by detecting the rigid and reliable points that satisfy the epipolar geometry. Experiments on the SCARED dataset demonstrate our superior performance over existing methods in novel view synthesis and pose estimation with high efficiency (Fig. 8). The related paper is published in MICCAI with open-source code.

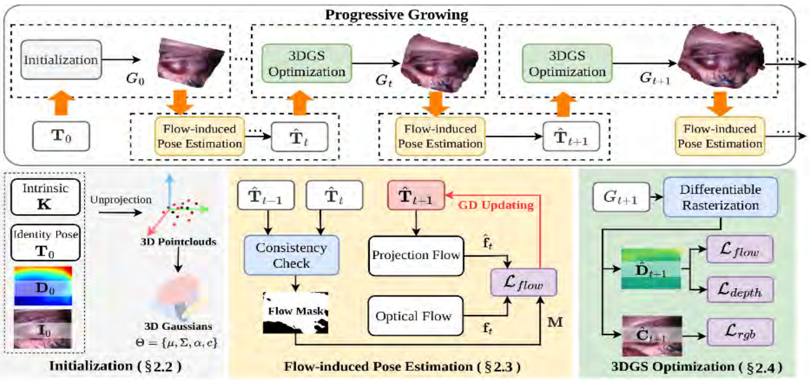

Fig. 7. Overview of the joint reconstruction and pose estimation from monocular image.

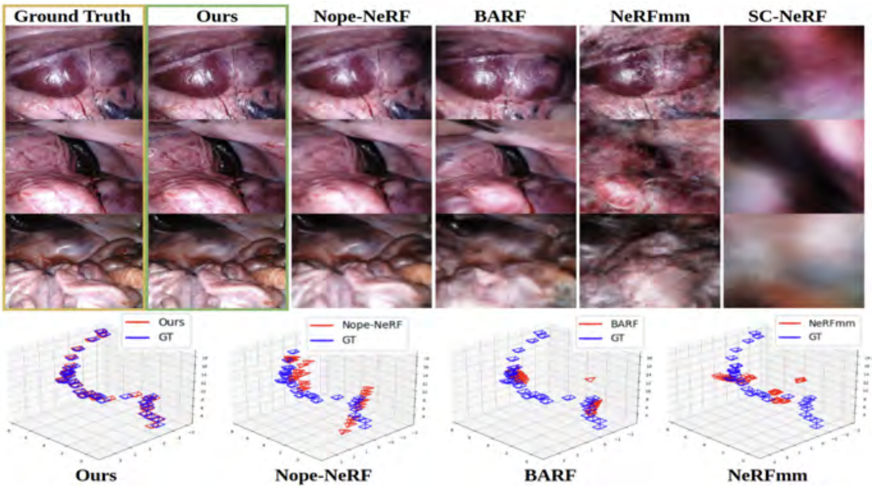

Fig. 8. Qualitative results of novel view rendering and pose estimation.

4. 3D shape sensing of flexible robots using FBG sensors

We have proposed a novel graph-based 3D-shape sensing of flexible medical instruments using multi-core fiber Bragg grating (FBG) sensors. Due to noisy signals, deformability of instruments, and environmental disturbances, conventional shape sensing methods using direct FBG measurements are far from accurate and stable, especially for long devices. To address the challenges, we propose a generic 3D shape graph to optimize the entire shape of flexible instruments globally and account for the accumulative errors in both spatial and temporal domains (Fig. 9). By leveraging the geometry configurations of FBG cores as the measurement model, a robust dynamic filtering approach is introduced for iterative curvature and twist estimation, which guarantees edge constraints of the graph-based shape optimization. Dedicated experiments are processed to validate our sensing approach in both structured and unstructured environments, where a robotic-assisted colonoscope system embedded with a multi-core FBG fiber is manipulated for the evaluations of bending as well as paths following in 3-D space. The results demonstrate the superiority of our framework as a promising solution for 3D shape reconstruction of flexible instruments and continuum robots in terms of accuracy, robustness, and fast response compared to state-of-the-art works (Fig. 10). The related works of shape sensing have been published in robotic conference and journals, including IROS, RA-L, and TMRB.

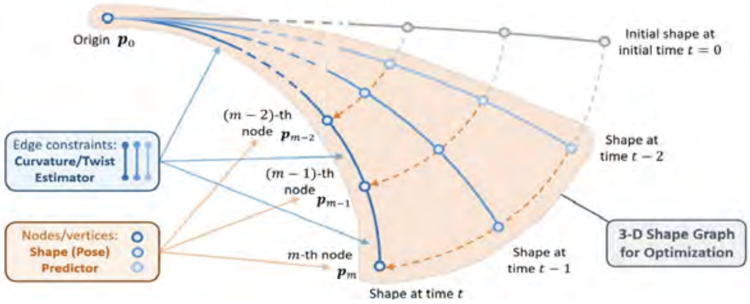

Fig. 9. 3D shape graph for shape optimization

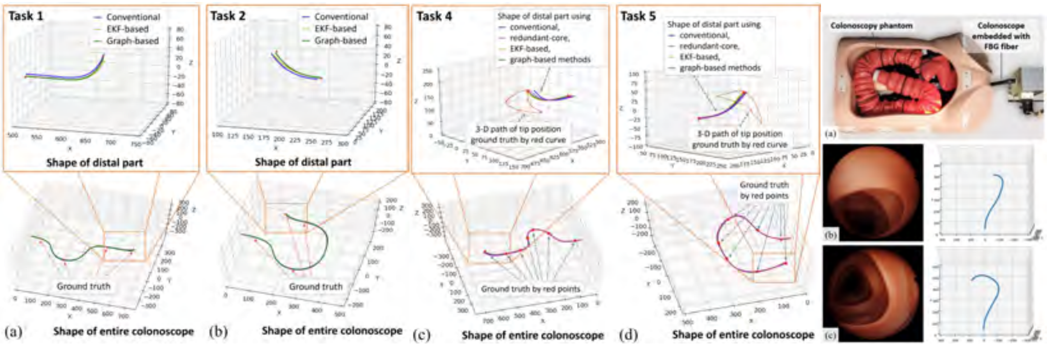
Fig. 10 Illustration of shape sensing results

Topic 2: Image-guided Surgery Planning and Navigation

1. Learning-based laparoscope motion planning and navigation

We developed several image-guided frameworks for operating laparoscope to provide proper views for surgeon's operations across various surgical scenarios (Fig. 11). Our team designed a data-driven approach utilizing a self-designed monocular RoboDepth model to estimate instrument depth and achieve 3D laparoscope motion control while addressing misorientation effect. Furthermore, to enhance control intelligence and facilitate learning of motion control directly from surgical videos, we developed a ConvLSTM-based network that can learn laparoscope motion at feature leve, such as optimal flow. Besides, we explored an efficient reinforcement learning (RL) paradigm through a shape-preserving trajectory augmentation for surgeon's demonstrations. To ensure the control safety in surgery, we developed a GMM-based framework with a heuristic decision algorithm for predicting the optimal target and the future trajectory in real-time while ensuring effective collision avoidance. The related works have been published in high-impact journals like IEEE Robotics and Automation Letters (RA-L) and top robotics conferences, including ICRA and IROS.

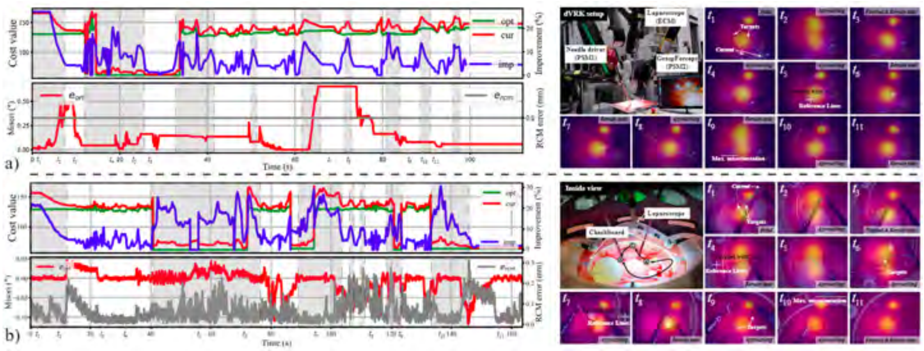
Fig. 11. Experiments for FoV control in (a) the surgical dVRK system and (b) the general robotic laparoscopy system.

2. Development of the autonomous navigation system of flexible endoscope

We proposed a data-driven framework with self-contained visual shape fusion for autonomous intelligent navigation of flexible endoscopes requiring no priori knowledge of system models and global environments. Based on the fiber Bragg grating (FBG) sensors, we developed several shape-sensing approaches, including EKF-based, and graph-model based methods, to determine the shape of the flexible endoscope. Then we implemented shape control for the flexible endoscope that can online estimate the unknown model of continuum robot against unexpected disturbances, exhibiting adaptive behavior to unmodeled systems without priori data exploration. To prevent unnecessary and excessive interactions with surrounding anatomy, an energy-motivated shape planning algorithm is introduced. The proposed system significantly reduced elastic potential energy (e.g., bending/torsion energy) in completing navigation tasks (Fig. 12) compared with that without shape planning, thus prevent unnecessary and excessive elastic contact forces on surrounding anatomy. The related works have been published in high-impact journals like Soft Robotics, IEEE Transactions on Medical Robotics and Bionics, IEEE Robotics and Automation Letters (RA-L) and top robotics conferences, including ICRA and IROS.

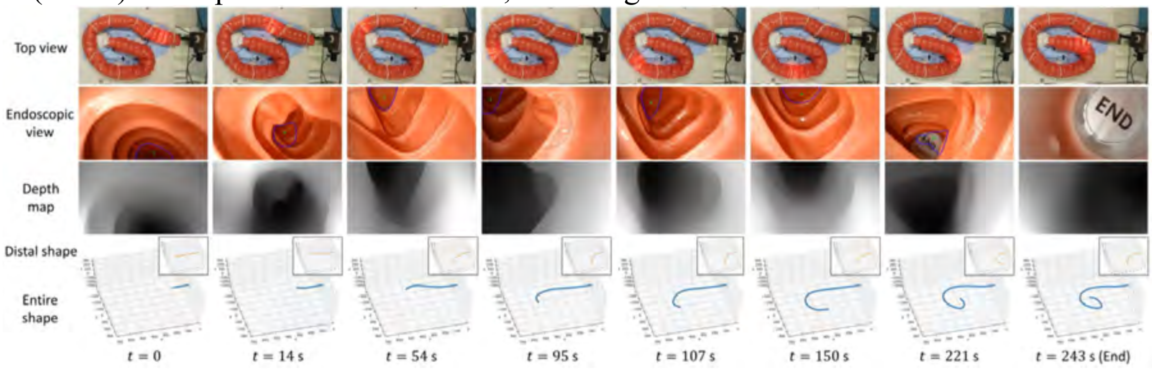

Fig. 12. Experiment snapshots: top view, endoscopic view, depth map, and FBG shapes of colonoscope and distal part.

3. Development of camera navigation based on online 3D reconstruction

We improved the real-time reconstruction system to densely build 3D surgical scenes from a stereo laparoscope and furthermore applied it to the navigation of laparoscope. The workflow of the proposed framework is demonstrated in Fig. 13. The learning-based depth estimation module is trained using supervised and unsupervised methods from surgical data for dense depth computation per single frame, followed by the dense visual reconstruction algorithm to reconstruct the entire surgical scene. Based on the reconstructed dense 3D structure, a laparoscopic localization module is proposed to achieve coarse-to-fine pose estimation. We evaluate the accuracy of the proposed reconstruction and localization module on the SCARED dataset, our in-vivo DaVinci robotic surgery dataset, as well as self-collected ex-vivo phantom and tissue-based data. Fig. 14 shows the 3D reconstruction results on different dataset, which qualitatively proves that the proposed method is accurate. The related works are published in IEEE Transactions on Biomedical Engineering (TBME), IEEE Transactions on Automation Science and Engineering (TASE), and top robotics conferences including MICCAI, IROS, and received the Finalist of Young Scientist Publication Award of MICCAI.

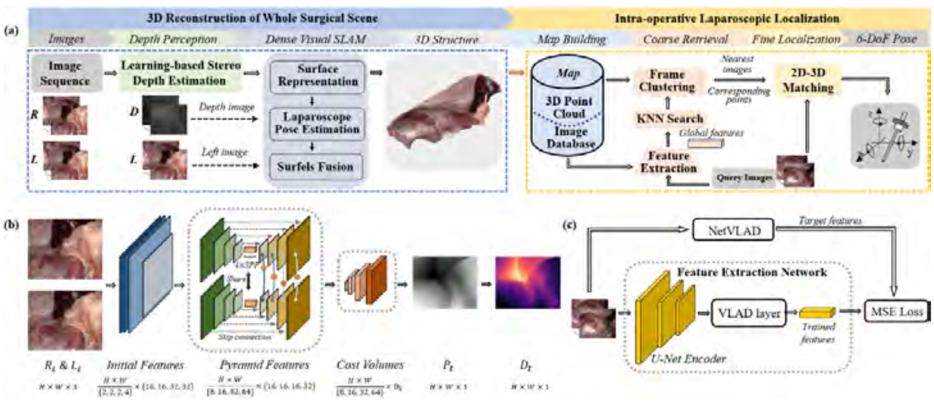

Fig. 13. Overview of the proposed framework. (a) Workflow our proposed stereo dense reconstruction method and its application to laparoscope tracking. (b) The process of the learning-based depth estimation module. (c) The training workflow of the feature extraction network in laparoscopic localization.

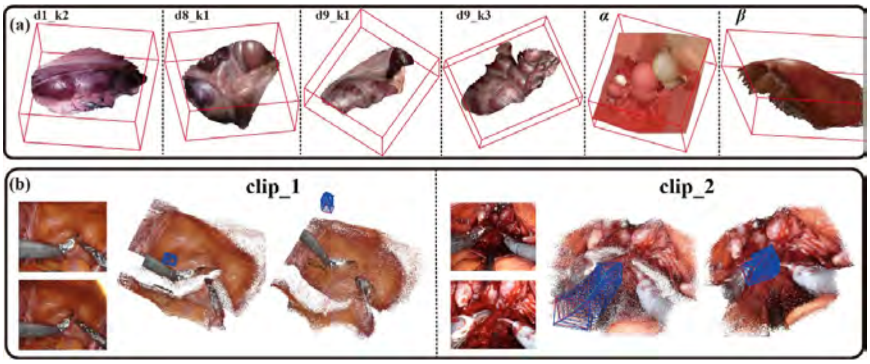

Fig. 14. Qualitative evaluation results on the SCARED, ex-vivo, and in-vivo dataset.

4. Development of the data-driven surgical planning system

We have developed several data-driven approaches for surgical planning across various surgical systems. To address cases with deficient visual features in optical camera-based soft robot navigation, we proposed fusing visual information with sparse strain data collected from FBGs. Utilizing the proposed online learning algorithm and simultaneous localization and mapping (SLAM), the FBG-based pose estimator can be trained and refined directly using data-driven fashion. We also introduced a hybrid controller that combines kinematics with data-driven algorithms for target tracking. The actual tracking trajectory could keep convergent to the desired even in cases involving external obstacles (Fig. 15). This work is published in the top-tier robotics journal IEEE Transactions on Robotics (TRO).

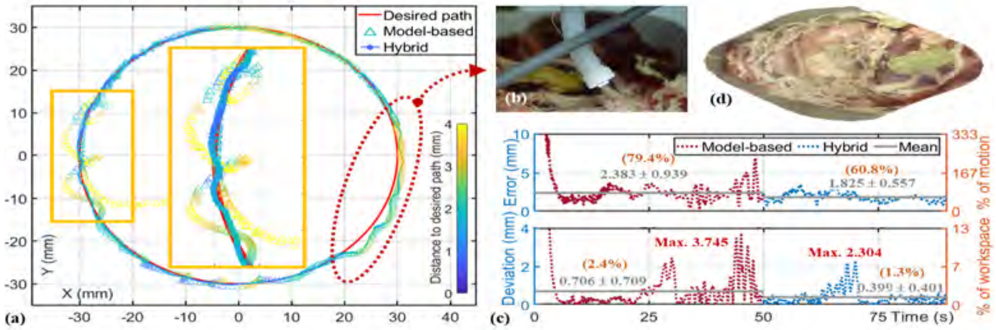

Fig. 15. Tracking performance in the swine-viscera-constructed abdominal simulator. **(a)** Trajectories of model-based (1st cycle) and hybrid (2nd cycle) controllers are plotted. An ellipse means the area that **(b)** a fixed aluminum rod limited one-side robot bending. **(c)** Tracking error and path deviation. **(d)** Image-stitched figure.

Second, to facilitate intelligent robotic manipulation in magnetic resonance imaging (MRI)-guided transoral laser microsurgery, we proposed a machine learning-based controller to enable accurate visual servoing of the laser spot along a path prescribed in situ on the camera view. The controller was initialized by training a neural network (NN) with time-varying 2D laser spot displacements and soft actuation status as its input, and the corresponding actuation changes as its output Fig. 16. Levenberg-Marquardt backpropagation was used to train the network parameters. The trained NN model enables output prediction at high frequency (> 100 Hz) for real-time robot control. Combined with the learning-based controller, accurate laser spot manipulation was achieved, with a mean tracking error < 200 μm in the path after tasks. This works has been published in the top-tier robotics journal of Science Robotics and wins HKU Research Output Prize.

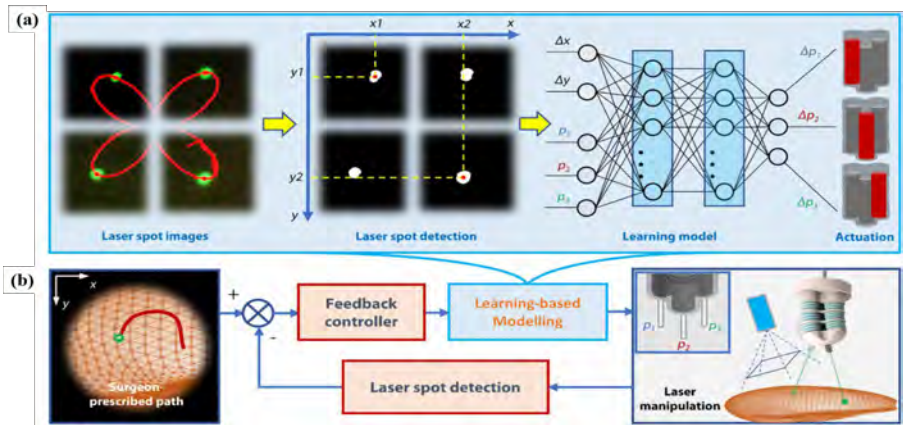

Fig. 16. Architecture of the proposed learning-based controller. **(a)** Overview of the learning-based model. The laser spot position in the camera view is varied by the laser manipulator. 2D displacements of the laser spot, along with the soft actuation states, act as inputs of a multilayer perceptron, which map to the actuation changes of each chamber. **(b)** The feedback control loop. With this learned inverse mapping, the proposed eye-to-hand visual servoing controller allows laser steering along paths prescribed in situ by the operator.

5. Development of the image-based surgical navigation system

We developed a normal-vector-assisted rigid registration method considering isotropic and anisotropic positional uncertainties for human femur model for surgical navigation in computer-assisted orthopedic surgery. We established the Bayesian coherent point drift framework that considers uncertainties with both positional and normal vectors, which are both generalised to anisotropic level. A two-stage non-rigid point set registration method is then developed, where the normal vectors are utilised in the first stage and the anisotropic uncertainties are considered in both stages. The proposed method can achieve the rotational and translation error values being 1.1 degree and 0.48 mm respectively, under 90% outliers. The superior performance in terms of robustness to noise and outliers outperforms existing state-of-the-art approaches for improved performance in robot-assisted orthopedic surgery, as shown in Fig. 17. The related works have been published in high-impact journals like IEEE Transactions on Automation Science and Engineering (TASE), IEEE Robotics and Automation Letters (RA-L).

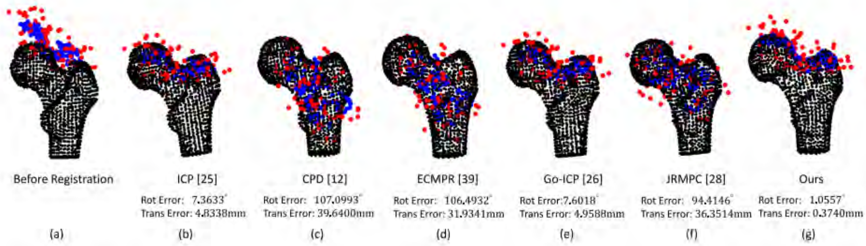

Fig. 17. The registration performances on the human femur model point sets (PSs). (a) The preoperative and intra-operative PSs before registration. The two PSs after registration using state-of-the-art methods (b-f) and our method (g). The black points represent the pre-operative PS, the blue shows the intra-operative inlier points while the red shows the intra-operative outliers.

Topic 3: Image-Based Motion/Action Control

1. Development of model-free controller of soft objects

We developed several image-guided controllers for manipulating soft objects, including soft tissues (Fig.18) and flexible robots (Fig.19). Our team designed a series of model-free controllers utilizing various visual measurements, such as 2D images, stereo images, and even raw point clouds. The control laws incorporate online learning and adaptation to handle unknown physical and geometric object models. Additionally, these control laws are designed with proven stability to ensure accuracy and safety, allowing us to effectively address occlusions and internal/external disturbances. The related works have been published in high-impact journals like IEEE Transactions on Robotics (TRO) and the International Journal of Robotics Research (IJRR), and we have been invited to present our work at top robotics conferences, including ICRA and IROS.

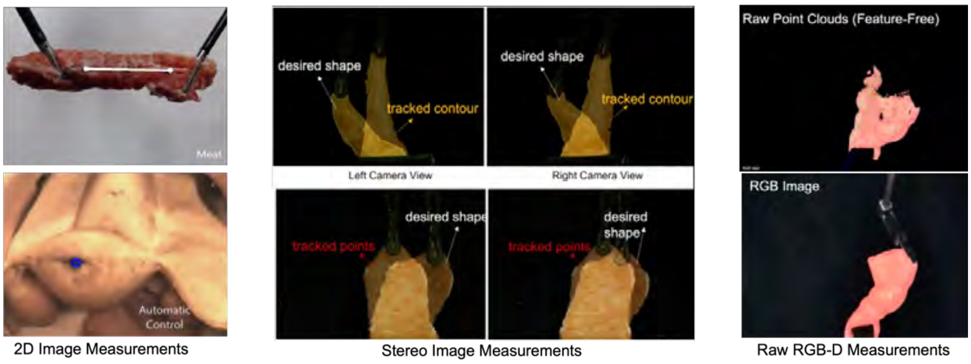

Fig. 18. Model-free deformation control of soft tissues

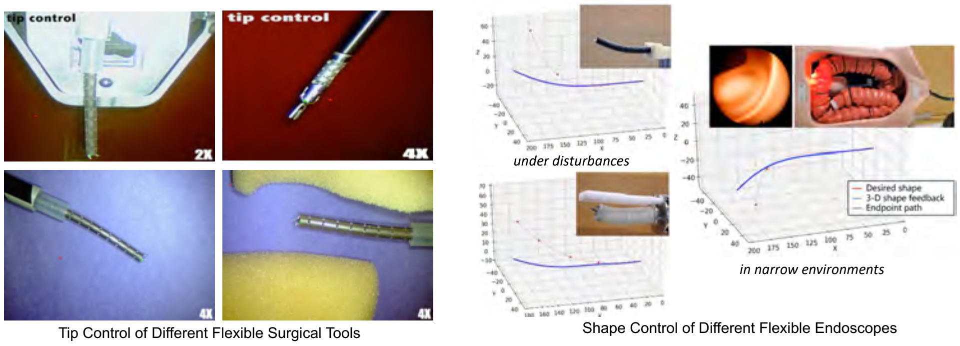

Fig. 19. Model-free deformation control of soft robots

2. Development of image-based coordination control of surgical robots:

We designed algorithms for robot-camera calibration in tightly constrained environments, enabling online calibration of robotic instruments without requiring models of the instruments or a large-scale data acquisition process (Fig. 20). Furthermore, we developed several frameworks for coordinating multi-arm robotic systems in complex surgical tasks (Fig. 21), including dual-arm cooperative needle insertion, three-arm cooperative needle insertion, and dual-arm cooperative suturing. Related works have been published in high-impact journals such as IEEE Transactions on Robotics (TRO) and the International Journal of Robotics Research (IJRR), and our team members have been invited to present these advancements at leading robotics conferences like ICRA and IROS.

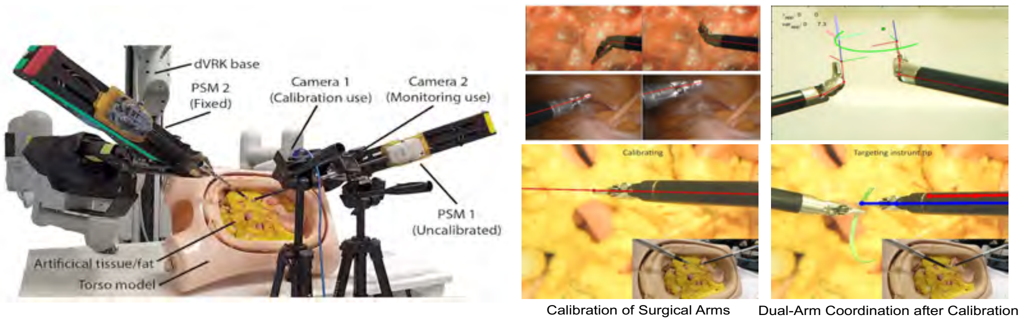

Fig. 20. Robot–camera calibration in tightly constrained environments

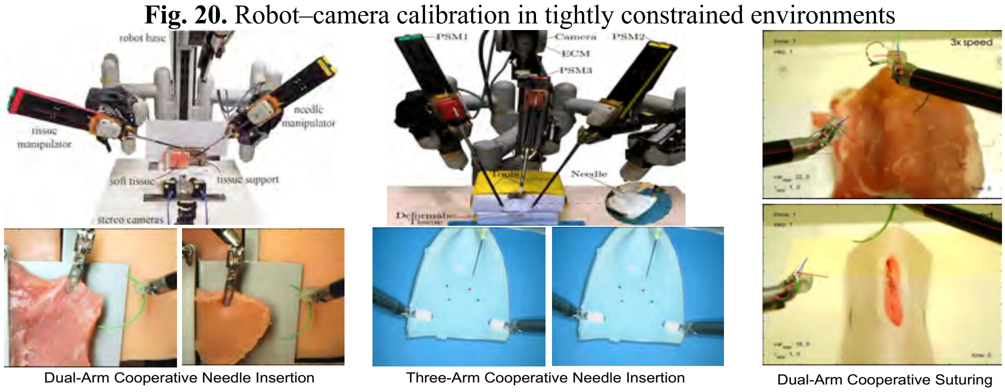

Fig. 21. Coordination control of multi-arms for task execution

Topic 4: Robotic Surgical Intelligence

1. Large-scale surgical video dataset development

We developed and released the first integrated dataset (named AutoLaparo) with multiple image-based perception tasks to facilitate learning-based automation in hysterectomy surgery (Fig. 22). It provides rich information to support context-awareness towards advanced computer-assisted minimally invasive surgery. Our AutoLaparo dataset is developed based on full-length videos of entire hysterectomy procedures collected from Prince of Wales Hospital, Hong Kong. Specifically, three different yet highly correlated tasks are formulated in the dataset, including surgical workflow recognition, laparoscope motion prediction, and instrument and key anatomy segmentation. In addition, we provide experimental results with state-of-the-art models as reference benchmarks for further model developments and evaluations on this dataset. The dataset and code are public available for academic research with over 200 downloads, and papers using this dataset are published in MICCAI, RAL, etc.

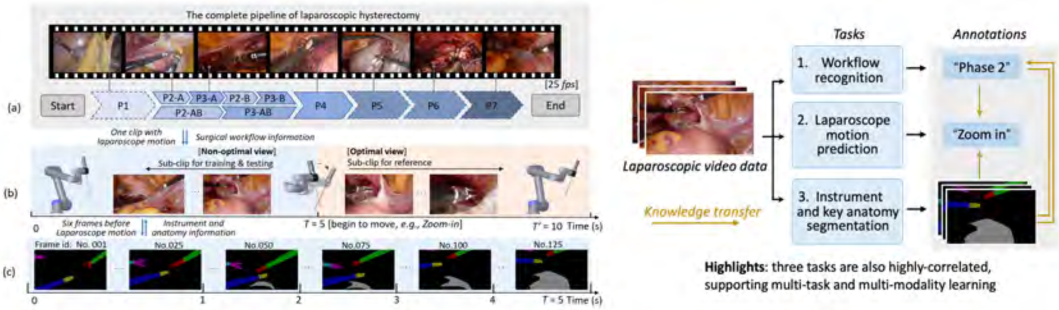

Fig. 22. Overview of the proposed surgical dataset with multi-tasks.

2. Learning-based surgical scene perception and understanding

- Surgical workflow recognition

We have developed several methods for surgical workflow recognition (Fig. 23), aiming to develop context-aware computer-assisted systems in the operating theatre. Specifically, we propose a novel end-to-end temporal memory relation network (TMRNet) for relating long-range and multi-scale temporal patterns to augment the present features. Besides, we present a novel multi-task recurrent convolutional network with correlation loss (MTRCNet-CL), which leverages task relatedness to simultaneously improve the tasks of surgical workflow recognition and tool presence detection. Furthermore, we are the first to apply Transformers in surgical workflow analysis to leverage complementary spatial and temporal features for accurate surgical phase recognition. The related papers on the surgical workflow recognition are published in MICCAI, TMI, MedIA, etc.

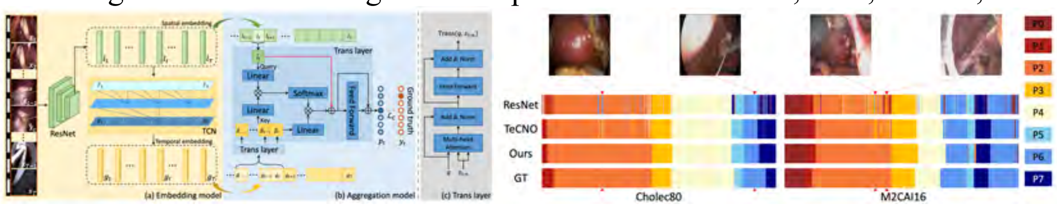

Fig. 23. Overview of the proposed model and results for surgical workflow recgnition.

- Surgical gesture recognition

We propose a novel online approach of multi-model relational graph network (i.e., MRG-Net) to dynamically integrate visual and kinematics information through interactive message propagation in the latent feature space (Fig. 24). Specifically, we first extract embeddings from video and kinematics sequences with temporal convolutional networks and LSTM units. Next, we identify multi-relations in these multi-modal embeddings and leverage them through a hierarchical relational graph learning module. This work is published in ICRA 2021 and received the Best Paper Award in Medical Robotics.

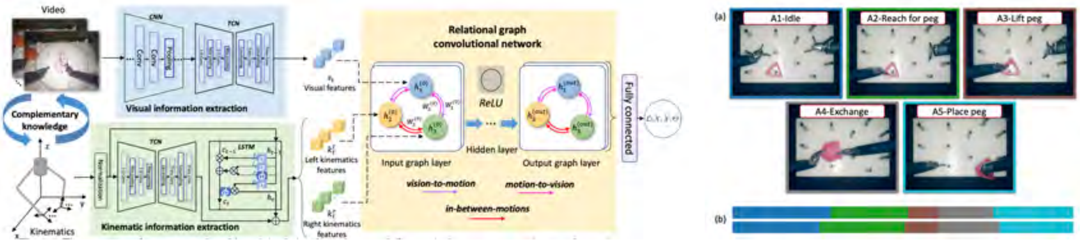

Fig. 24. Overview of our proposed network for surgical gesture recognition.

- Surgical scene segmentation

We develop novel methods for surgical scene segmentation (Fig. 25), in order to precisely parsing the entire surgical scene. We propose a novel method for surgical instrument instance segmentation, where we optimize the Mask R-CNN with anchor optimization and improved Region Proposal Network for instrument segmentation, and perform cross-dataset evaluation with different sampling strategies. In addition, we propose a novel framework STswinCL that explores the complementary intra- and inter-video relations to boost segmentation performance, by progressively capturing the global context, which consistently exceeds previous state-of-the-art approaches. Related works are published in TMI, IJCAI, etc.

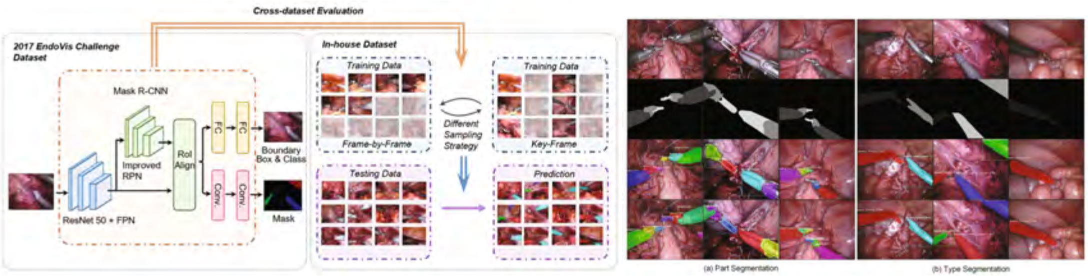

Fig. 25. Overview of the proposed surgical scene segmentation model and results.

3. RL-driven platform for surgical robot learning

We designed SurRoL (Fig. 26), a simulation platform that is dedicated to surgical embodied intelligence with strong focus on learning algorithm support and extendable infrastructure design. With which we hope to pave the way for future research on surgical embodied intelligence. In SurRoL, we create assets of surgical tasks with the help of the powerful 3D modeling tool Blender, and then generate relevant collision models and urdf description models at the same time for physical modeling in the simulation environment. In addition, we have established a spectrum of tasks given the dexterity and precision properties in the surgical context, including fundamental action tasks, ECM fov control tasks, and basic surgical robot skill training tasks. To incorporate human control of surgical robots in the simulator, we develop a manipulation system with human input devices. Besides, our platform enables the smooth transfer of learned skills from the simulation to the real world. This platform is open-source, and our related papers are published in ICRA, IROS, ISMR, RAL, etc.

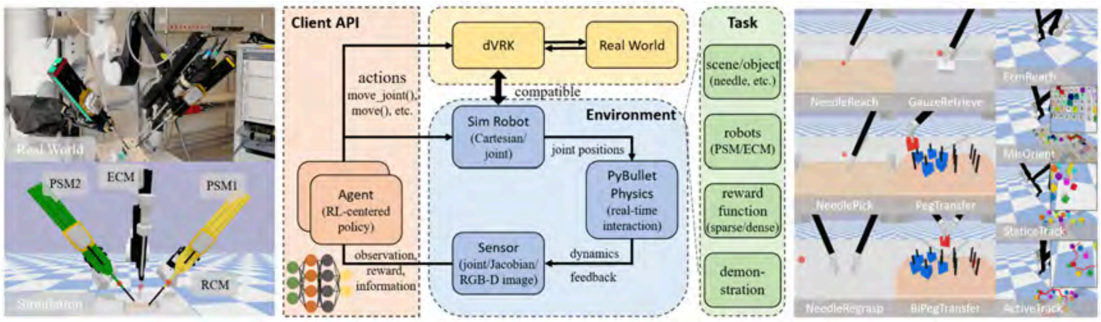

Fig. 26. System design of SurRoL for dVRK compatible environments and supports ten common surgical tasks.

Topic 5: System Integration and Case Studies

1) Development and commercialization of multi-port endoscopic surgical robot system

In addition to improving the dVRK, by integrating the modular joints, the instruments, the software technology, the control and planning methods, human-robot interactions, etc. developed in this project, we have designed and built a novel multi-port surgical robot, together with a start-up company **Cornerstone Robotics Limited** co-founded by the team members: Prof. Samuel Au, Dr. Zerui Wang, Prof. Yunhui Liu and Prof. Philip Chiu. The developed Sentire endoscopic surgical system includes a surgeon master console, multi-arm patient-side manipulators, and an integrated robot and endoscopic image data processor (Fig. 27). The performance of our own surgical robot has been further examined by leading surgeons in Hong Kong and Mainland through in-vivo experiments (Fig. 28). All the surgeons highly commented the performance of our robot and considered it at similar levels to that of the da Vinci robots. Multi-center clinical trials in Beijing, Shanghai, and Zhejiang, have been completed with 100 % success rate with smooth procedures, zero surgical referral rate, nor any other complications. The representative procedures covered include prostatectomy, cholecystectomy, bladder removal, and lower GI procedures. The National Medical Products Administration (NMPA) registration approval has been received for the usage in Mainland and Hong Kong.

Fig. 27. Sentire endoscopic surgical system developed together with Cornerstone Robotics Limited.

Fig. 28. In-vivo experiments using Sentire endoscopic surgical system.

2) Development and commercialization of a flexible miniature surgical robot

The team integrated the technologies into the development of a flexible surgical robot with a set of thin and dexterous robotic instruments that can be passed through the instrument channels of conventional endoscopes currently used in clinical practice. This system provides long, flexible, and miniature robotic arms with five degrees of freedom (DoFs) per arm in order to enhance tissue traction and instrument triangulation. Each robotic arm measures < 2.8 mm in diameter which is thin enough to be seamlessly compatible with conventional endoscopes. Lightweight console and "free-floating" pen controllers allow surgeons to transit to and from endoscope control in order to improve patient access (Fig. 29). The team members Prof. Ka-Wai Kwok, Prof. Jason Chan and Prof. Yunhui Liu set up a start-up Agilis Robotics Limited to commercialize the flexible miniature surgical robot. Animal trial of the flexible surgical robot was performed at Prince of Wales Hospital (PWH). Two surgeons were asked to perform en-bloc resection of bladder tumors (ERBT) with the robotic system (Fig. 30), and they could perform the resection successfully using the arms for 30 mins. The experiments validated the effectiveness of the robot in the confined workspace and made important steps to clinical experiments.

Fig. 29. A dexterous and flexible miniature surgical robot developed together with Agilis Robotics Limited.

Fig. 30. The flexible miniature surgical robot in animal study including patient-side setup and surgeon's master console.

3) Development and validation of an interactive one-surgeon-four-arms system

By integrating image-based tracking and perception with surgical robots, we have developed an interactive one-surgeon-four-arm system that provides a surgeon with two additional arms in the laparoscopic hysterectomy. In the system, a uterus manipulation robot and a laparoscopic manipulation robot assist the surgeon in the surgical procedures by providing automated or interactive control of the uterus and the laparoscope, respectively. The performance of the robotic system in laparoscopic hysterectomy has been validated by cadaver experiments at PWH (Fig. 31). We also obtained the clinical trial approval of the robotic uterus manipulator at International Peace Maternity and Child Health Hospital (IPMCH), Shanghai, and conducted two experiments on human subjects: including a total laparoscopic hysterectomy and an adenomyoma reduction surgery (Fig. 32). We have applied for clinical experiments in Hong Kong, and electromagnetic compatibility (EMC) tests have been passed. Further development is being conducted towards commercialization.

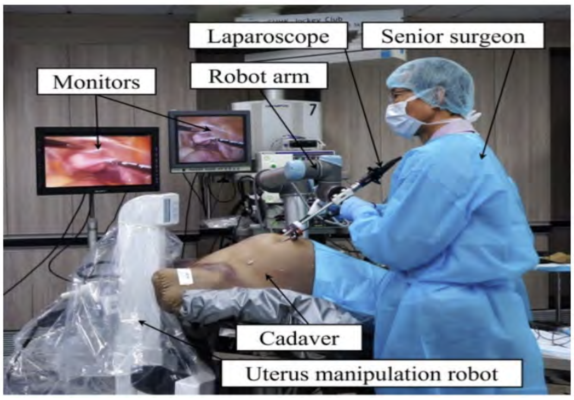

Fig. 31. The one-surgeon-four-arm system for laparoscopic hysterectomy.

Fig. 32. Operating room layout for testing of our robotic uterus manipulator in clinical trials.

6.2 What was the added value of the TRS funding, rather than standard project grant funding?
(For example, could this work have been achieved with other funding scheme, such as the General Research Fund or Collaborative Research Fund? If not, why?)

No, this work could not have been achieved with the other funding schemes. The added value of TRS funding lies in its strategic focus on themes of long-term importance to Hong Kong's development, enabling the integration of advanced robotics and imaging technology in surgical procedures. Unlike standard project grants, TRS funding facilitated collaboration among global experts from engineering and medicine, fostering innovation in robotic surgery that may not have been possible through the General Research Fund or Collaborative Research Fund. The ambitious scope and scale of the project, including the development of intelligent surgical robots and an open-source learning platform, required dedicated resources and a collaborative framework that TRS funding uniquely provided.

6.3 If the project has not met its original objectives, why?

The project has met its original objectives.

6.4 (a) Please provide details of each peer-reviewed journal publication arising <u>directly</u> from this project by completing the table at **<u>Annex</u>** *(one for each publication)*.

Please refer to Annex and Appendix 1.

(b) Please provide details of recognised international conference(s) in which paper(s) related to this project was/were delivered by completing the following table:
<u>(Please attach a copy of each conference abstract)</u>

Please refer to Appendix 2.

(c) RGC funding should have been acknowledged in all publication(s)/conference papers listed in (a) and (b) above. If no acknowledgement has been made in any of the publications/ papers, please indicate and provide explanations.

Please refer to Appendix 1 and 2.

6.5 To what extent this project has strengthened inter-institutional collaborations and other partnerships?

The project has significantly enhanced inter-institutional collaboration by establishing the Multi-scale Medical Robotics Center, involving local institutions such as The University of Hong Kong, City University of Hong Kong, and Prince of Wales Hospital. It has also formed international partnerships with prestigious institutions, including Johns Hopkins University and Imperial College London.
Building on this foundation, the follow-up AoE project, “AI-Powered Surgical Robots,” further strengthens these collaborations by incorporating The Hong Kong Polytechnic University and expanding the network to include the Technical University of Munich, University College London, and Shanghai Jiao Tong University, alongside hospitals in Hong Kong and mainland China. This collaborative framework fosters innovation and resource sharing in surgical robotics, creating a robust collaborative ecosystem for advancing the field.

6.6 Research students trained (registration/awards):
Please refer to Appendix 3.

6.7 Specific products (e.g. software or netware, instruments or equipment developed):
The technologies developed in this project have led to the following products, which have been developed and commercialized by the start-ups founded by the team members:
1. A novel multi-port endoscopic surgical robot system for minimally invasive surgery, which has been developed and commercialized by CornerStone Robotics Limited (co-founded by the team members: Prof. Samul Au, Dr. Zerui Wang, Prof. Yunhui Liu and Prof. Philip Chiu), and approved by the National Medical Products Administration (NMPA) in September 2024 for its usage in Mainland and Hong Kong;
2. A flexible miniature surgical robot for surgery in confined space (endoscopic surgery, etc.), which has been developed and commercialized by Agilis Robotics Limited (co-founded by the team members: Prof. Ka-Wai Kwok, Prof. Jason Chan and Prof. Yunhui Liu); and
3. A novel surgical robot for gynaecological procedures including uterus manipulation in hysterectomy, which is being further developed to products by our Ph.D. students and staff.

6.8 Other education activities and/or training programmes developed:
Our team has actively developed various educational activities and training programs to enhance knowledge and practical skills in surgical robotics. We offer internship opportunities for both local and non-local students, allowing them to gain hands-on experience in surgical robotics. We also promote international exchange, with PhD students engaging in academic collaboration with Johns Hopkins University. Additionally, we have developed an open-source platform for surgical robot learning that enables users to perform surgical actions via human interaction devices and integrates AI with augmented reality to automatically generate surgical guidance for robotic surgery education. Besides, our spin-off, Cornerstone Robotics, have co-hosted specialized robotic surgery training program with the University of Hong Kong–Shenzhen Hospital, providing hands-on training in laparoscopic robotics for surgeons, and also partnered with CUHK-Shenzhen MEDICINE to establish a “Minimally Invasive Surgery and Surgical Robot Teaching Base” for joint efforts in platform construction, educational training, and research.

6.9 Please highlight any deliverables indicated in the project implementation timetable endorsed by the RGC which have not been covered or achieved as per sections 6.1 to 6.8 above, and explain/ elaborate.
All deliverables were covered and achieved.

Project Management

6.10 Please elaborate how the PC has played his/her role in coordinating and managing the project. The roles of the PC include i) project planning, ii) progress monitoring, iii) resources management with help from the management committee, and iv) participation in the research topics. In the project planning, he divides the research project into small research topics, set the feasible goals and timeframes, and assigns tasks to the team members. In progress monitoring, he traces the project progress by reading the progress reports, regularly (at least one a month) meeting with the Co-PIs of the research topics, the research staff and the students. In resources management, he coordinates the purchase of the major equipment and proper use of the equipment by the research members, and oversees the project expenditures, ensuring that the fund is properly spent as budgeted. In research participation, he takes parts in technology development in the five research topics. He also frequently exchanges ideas with local and overseas scholars and surgeons to obtain the most up-to-date information to refine the research topics and their objectives. Moreover, during the period of disturbance with social events and disruption due to the pandemic situation, the PC spent tremendous efforts to ensure progress of the research as scheduled as possible.

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7. Awards and Recognition

7.1 Have any research grants been awarded that are directly attributable to the results obtained from this project?

An Areas of Excellence Scheme project named "AI-Powered Surgical Robots" has been approved by RGC and granted with HKD 96.809M, which is directly attributable to the results obtained from this project.

7.2 Have any project team members participated as invited speakers in or organisers of international conferences as a result of this project?

Please refer to Appendix 4.

7.3 Have any project team members taken leadership positions in editorial boards, scientific and professional organisations?

Please refer to Appendix 4.

7.4 Any documentary proof of the application of technologies arising directly from this project?

We have eight patents and two licensing documents arising directly from this project. Please refer to Appendix 5.

7.5 Other awards and recognitions as a result of this project (please specify):

Please refer to Appendix 4.

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8. Impacts

8.1 What are the current and expected impacts of the project on the long-term development of Hong Kong (social or economic development, e.g. patent, technology transfer, collaboration with external organisations, etc.)?

Multiple surgery-assisted robot prototypes have been developed, covering interventions ranging from laparoscopic surgeries to stereotactic neurosurgery, transoral laser microsurgery, then to cardiac ablation and percutaneous liver tumour biopsy. The multi-port surgical robot and the flexible miniature surgical robot are set to be commercialized by our start-up companies. Cornerstone Robotics has developed the endoscopic surgical system entirely in-house for conducting soft tissue surgery and has completed the clinical trials in both Hong Kong and Mainland, while Agilis Robotics has developed highly miniaturized and flexible robotic instruments for transforming endoluminal surgery and empowers surgeons to intuitive remove cancer in both the urinary tract and gastrointestinal tract without any external incisions. The success of the commercialization is positioning Hong Kong as a key player in surgical robotics research, production, and commercialization across China, Asia, as well as the world. Further advancements are expected to generate further IP invention. With support from industries, further technology transfer and collaboration among academia and industries will be promoted, including further development within the future AoE project and collaboration with the MRC organization. The impact will also be on social well-being, from better treatments brought by surgical robots in various interventions.

8.2 Others (please specify):
N/A

9. Sustainability of the Project

9.1 Whether there are new ideas evolved directly from this project?

We have developed a new conceptualization in the fundamental technologies that advance the level of autonomy in robotic surgery. In this TRS project, we initially hypothesized that four technical elements are essential to achieve autonomous robotic surgery: sensing and perception, planning and navigation, image-guided control, and robotic surgical intelligence. By integrating these technologies into our designed one-surgeon, four-arm system for hysterectomy, we achieved level-2 autonomy in cadaver studies. To attain a higher level of autonomy, we redefined the four fundamental technologies, which includes AI-based perception, AI-powered planning and navigation, skill learning, and data-driven control.

We have built three new robot prototypes to achieve autonomous surgery to validate our proposed technologies and the new conceptualization. These prototypes include a general surgical robot for autonomous suturing, a flexible endoscopic robot for automated kidney stone removal, and a needle-based robot for prostate biopsy.

We are funded by a new AoE project (HK$96M) to validate the newly proposed methodologies and robot prototypes, starting in January 2025.

9.2 Whether there are new projects evolved directly from this project?

Two projects have evolved directly from this work. The first is "AI-Powered Surgical Robots", supported by the Areas of Excellence (AoE) Scheme 2024/25. This project aims to investigate next-generation AI-powered surgical robots capable of autonomously performing surgical subtasks or entire procedures. By advancing technologies in both AI and robotics, we seek to push the boundaries of surgical robots toward Level-3 autonomy and establish a world-renowned research centre for autonomous surgical robotics in Hong Kong.

The second project is the "Multi-Scale Medical Robotics Centre (MRC)," supported by AIR@InnoHK. The MRC laboratory aims to conduct translational research through R&D programs focused on endoluminal multiscale robotic platforms, a magnetic-guided endoluminal robotic

platform, and image-guided robotic interventions.
Both projects focus on surgical robots, but the AoE project places greater emphasis on exploring the fundamental technologies that advance autonomy in surgical robotics, while the MRC project focuses more on technology transfer and clinical translation.

9.3 Whether there are new collaborations developed directly from this project?
Compared to this TRS project, our new AoE project has established collaborations with 10 new Co-Principal Investigators (Co-PIs), including professors and surgeons specializing in data science, urology, radiology, artificial intelligence, and robotics. Specifically, they include Prof. NG Chi Fai from CUHK (Urology); Prof. WANG Jun from CityU (Data Science); Prof. CHU Winnie from CUHK (Radiology); Prof. LIU Lu from CityU (Biomedical and Mechanical Engineering); Dr. NAVARRO-ALARCON David from PolyU (Mechanical Engineering); Dr. LI Zheng from CUHK (Surgery); Dr. DOU Qi from CUHK (Computer Science); Dr. CHENG Shing Shin from CUHK (Mechanical and Automation Engineering); Dr. WANG Jiangliu from CUHK (Mechanical and Automation Engineering); and Dr. LIU Alex Qinyang from CUHK (Urology).

We have also developed new collaborations with 4 collaborators, including Prof. ZHANG Xu from the 301 Hospital, an Academician of the Chinese Academy of Sciences; Prof. LUETH Tim Christian from TUM; Prof. STOYANOV Danail from UCL; and Prof. WANG Hesheng from Shanghai Jiao Tong University.

9.4 Please give details on how much money and from which sources has been obtained/requested for the specific purpose of continuing the work started under this project.
RGC has granted an Areas of Excellence Scheme project named "AI-Powered Surgical Robots" with HKD 96.809M as the continuing project of this TRS project. The core objective of the project is to investigate AI-powered automation in robotic surgery based on multimodal information perception.

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10. Statistics on Research Outputs

(Please ensure the statistics in this section are consistent with the information presented in other sections of this report.)

	Peer-reviewed journal publications	Conference papers	Scholarly, books, monographs and chapters	Patents awarded	Other research outputs (please specify)	
					Type	No.
No. of outputs arising directly from this research project	68	33	0	8	N/A	N/A

11. Public Access of Completion Report

(PCs of projects funded in 2010/11 academic year or onwards are required to release the completion reports to the public through the RGC website. Completion reports containing information such as abstracts in non-technical terms, objectives, research output including the list of conference papers / publications / journals and research findings and contact information of PCs should be open to public access.)

Please specify the information, if any, that cannot be provided for public access and give the reasons.

Information that cannot be provided for public access	Reasons
N/A	N/A

12. The Layman's Summary

(describe in layman's language the abstracts and research impact of the project.)

Abstract:

The project has significantly enhanced surgical procedures through cutting-edge robotics and imaging technology. Leveraging Hong Kong's exceptional healthcare system, we focused on developing intelligent surgical robots that can assist surgeons and perform tasks autonomously, ultimately improving safety and efficiency for surgical treatments.

Key milestones were achieved in developing core technologies and integrating advanced robotic systems for surgical procedures. We created innovative methods for accurately sensing the surgical environment, planning complex surgeries, reliably controlling robotic motion, and facilitating surgical intelligence. Notably, an intelligent one-surgeon-four-arms system was integrated to provide surgeons with two additional arms for laparoscopic hysterectomy, enabling automated control of the uterus and laparoscope. We also developed a multi-port surgical robot for minimally invasive surgeries and a flexible miniature robot for endoscopic procedures, enhancing precision and automation. Additionally, we introduced SurRoL, an open-source platform for surgical robot learning. We conducted ex-vivo experiments with these robotic systems, and ongoing clinical trials at the Prince of Wales Hospital have shown promising preliminary results.

Throughout the project, worldwide experts from engineering and medicine worked together to tackle challenges in robotic surgeries. This project has significantly advanced the field of robotic surgery, setting the stage for future innovations and improved patient care.

Research Impact:

The project has significantly advanced surgical robotics, establishing Hong Kong as a leader in this innovative area. Its effects are felt across global reputation, medical outcomes, social benefits, and the economy.

1. Global Reputation
   Collaboration with esteemed international institutions has significantly enhanced Hong Kong's status in the global medical community. The project has resulted in the publication of high-impact papers in top journals and presentations at leading conferences, showcasing the region's commitment to cutting-edge research and innovation in healthcare technology. Furthermore, the establishment of the world-class Multi-scale Medical Robotics Centre in Hong Kong solidifies its influence and leadership in this advanced field.
2. Economic Impact
   The project has significant economic implications, focusing on translating advanced technologies into commercial products. It has led to the formation of two start-up companies and attracted local and global investments of up to $2 billion, creating approximately 100 high-skilled job opportunities in the healthcare and technology sectors.
3. Social and Medical Impact
   This initiative enhances regional healthcare by increasing access to innovative treatments and improving patient care. The project has markedly improved surgical precision and patient outcomes through advanced surgical robotic systems, which enhance control during minimally invasive surgeries, reducing complications and shortening recovery times. Furthermore, it has trained over 25 postdoctoral researchers and 50 graduate students, nurturing local talent and fostering innovation and technology development within the community.

In summary, the project has made a profound impact on multiple levels. The advancements in surgical precision and patient care not only enhance current medical practices but also lay the groundwork for future innovations. As the project continues to translate technologies into commercial products, it sets a strong foundation for the next generation of healthcare advancements, ultimately benefiting patients and the broader community.