Systems for handheld surgical robotics and man-machine OR teams

Auguste van Poelgeest, Dominik Kaltenbacher, Timo Cuntz, Christian Spindler, Arash Sanagoo, Jonathan Schaechtele and Andreas Rothfuss
Project Group for Automation in Medicine and Biotechnology
Fraunhofer IPA, Mannheim, Germany
Email: auguste.van.poelgeest@ipa.fraunhofer.de

***Abstract*—Medical robotics is an expanding field of research with more certified products entering the market and more technologies being developed. Given the number of surgical specialties and procedures, there is no one solution that would suit all applications. This paper focuses on the requirements and the development of systems for novel techniques in visceral surgery. Here the aim is to design surgical instruments with greater flexibility and degrees of freedom that are still intuitive to use.**

I. Introduction

The use of robot assistance is an increasing market with a lot of growth potential [1]. The only commercially available telerobotic system, namely the da Vinci platform, is still limited with regards to the range of procedures that it can perform [2]. Within this limited range, the number of robotically assisted procedures is increasingly growing regardless of the lack of clinical advantages over manual laparoscopic surgery [3]. The advantages such as 3D visualisation, improved dexterity, surgeon ergonomics and elimination of the fulcrum effect [2] outweigh the disadvantages such as the high cost, bulky size, and lack of tactile feedback [2].

Besides the growth in robot assisted surgery, developments in surgical techniques focus on making minimally invasive surgery even less invasive. This is achieved by Laparoscopic Endoscopic Single Site (LESS) surgery whereby all the instruments and the camera are entered into the patient through a single trocar in the abdominal wall. Another method is to access the abdomen via the esophagus, the rectum or the vagina and inserting the instruments and camera via an incision in one of these structures. For LESS surgery there are a few commercial systems available and various systems being developed [4]. Similarly, there are systems for NOTES available or under development [4].

Technological solutions could bring robot assisted surgery together with techniques such as NOTES to enable the full potential of this novel technique [5]. For LESS surgery there is also a great potential for combination with robot assistance as shown, experimentally by [6]. In this study, customised da Vinci instruments were used to carry out a gall bladder removal. Although feasible, it was evident that the da Vinci system was not designed for such a procedure.

The next sections discuss the requirements of robot assistance systems for NOTES and LESS and proposes technologies and methods to develop solutions that meet these requirements.

II. Requirements

As [7] identified, the instruments need to be more flexible and have a much greater range of motion from the point where they enter the abdomen. Also the instruments should not protrude out of the access port in a straight line more or less parallel to the port, but articulate away from the trocar. Finally, it was argued that if the instruments had different lengths, they could operate in different planes thus avoiding collisions. To be able to carry out standard procedures, the forces that are transferred through the instrument should not differ from those measured during ”normal” laparoscopic procedures. This means that the small flexible instruments should be able to transfer forces of approximately 30N [8]. With these force magnitudes, it is important that the surgeon has some tactile feedback in the instrument handle. The lack of haptic feedback has been identified as a current weakness of robot assisted systems. Experimental work has shown that the precision and control of instruments and flexible endoscopes is vastly improved by this feedback [9], [10]. Finally, the whole system consisting of instruments and their holders, a camera and its holder and the user interface devices should be small and light, and ideally be hand-held.

III. Solutions

A novel system where a robot and a surgeon work together to carry out LESS or NOTES surgery requires a number of technological advances. The instruments need to be highly manoeuvrable, generate relatively large forces for their size and ideally have flexible supply lines. This has led to the development of small hydraulic actuators.

Prototypes of miniature hydraulic cylinders and pneumatic muscles, see figure 1, have been manufactured from off-the-shelf components. Both actuator types were tested to establish the maximum pressure they could withstand, their force generation capacity, stroke, and in case of the cylinder, friction. The hydraulic cylinder had a piston diameter of 2.7mm and was sealed with an o-ring. It withstood pressures up to 200

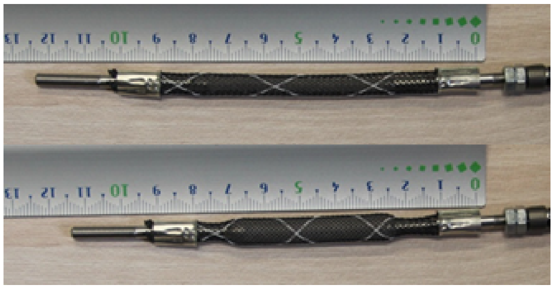

Fig. 1. Example of flexible, energy dense, pneumatic muscle actuator made from off-the-shelf components

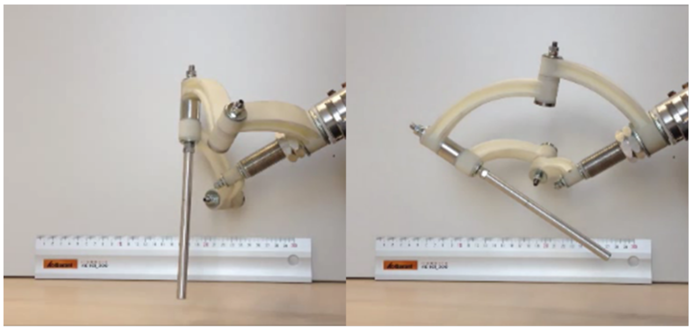

Fig. 2. Parallel kinematic system for instruments and scopes

bar at which point a force of 94N was measured. The seal friction at this presssure was measured at 2N, which was lower than expected from an o-ring. The working fluid was medical white oil, which is the hydraulic fluid that is proposed for the novel instruments. The pneumatic muscle prototypes were tested with both air and water as their working fluid. They could not withstand high pressures such as the cylinder: the connection between the flexible tube and the pressure supply would start to look. Nevertheless, a muscle actuator with an inner tube diameter of 1.5mm and outer tube diameter of 2.5mm tested with water generated a force of 30N with a supply pressure of 9 bar. These results have indicated that hydraulic drives are appropriate for this application. Another advantage of hydraulics provides is that the supply pressure is a direct indicator of the force generated at the instrument tip. In other words, this type of actuation enables a simple and safe implementation of haptic feedback. Finally, for robotic applications, hydraulics also have the advantage that its dynamics are well understood as well as potential friction losses. This means that robot control systems can be developed rapidly and with a high level of certainty.

To hold and move instruments or cameras, a spherical parallel kinematic system has been developed, see figure 2. It is small for the range of motion it has, the parallel arms ensure increased robustness over a serial kinematic system and the pivot point of the instrument motion is mechanically defined. Its kinematic and dynamic characteristics are currently being analysed and the design is being optimised for a range of parameters. One of these parameters is the range of motion. Ideally, this is a large as possible inside the patient, but as small as possible outside the patient. Another parameter is the sensitivity and relative linearity between the motion of the drives and the motion of the instrument. Here the ideal case is that the drive requires a large displacement for the instrument to move by a small amount. The goal is to find the best compromise between these optimisation parameters, which can be conflicting.

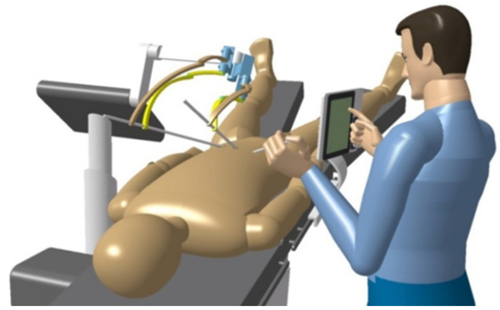

Fig. 3. Example of a Man-Machine Team

Once all the components have been characterised and optimised, the goal is to integrate them into a flexible surgical robotic assistance system. Starting with a typical laparoscopic intervention with 4 incisions, the parallel kinematic system is used to hold the endoscope and one rigid instrument while the surgeon holds the two other instruments. The challenge is to develop a user interaction method for handsfree control of the camera angle and rigid instrument orientation. The next step is combine the components to enable Single Port surgery. The two parallel assistive robots need to be dimensioned to ensure maximum motion while avoiding collisions. In this application, the surgeon will require flexible instruments to reach all structures. These are the flexible handheld instruments descibed previously with equiped mechatronic input devices. Figure 3 illustrates this vision.

IV. Conclusion

There is a great potential to develop technology for man-machine OR teams that have been designed to carry out novel operating techniques such as NOTES and LESS. This type of system has many requirements to meet, but they can be addressed by developing modular solutions for the instruments, the instrument manipulators and the user interfaces and all the other components. These modular solutions can finally be combined to form a flexible, small and lightweight, user-friendly assembly that can be used for routine as well as complex surgeries. Hydraulic actuators form part of this modular solution to provide more flexibility to the system, while meeting the force generation requirements. Parallel kinematic devices form the basis of the small and lightweight instrument manipulator modules. Both these modular systems have so far shown promising results.

V. Future Work

Once the modules for the instruments and their parallel robot manipulators are finished, the challenge is to ensure

their interaction with the user is intuitive. The first step is to establish what constitutes a good interface. For this purpose, computer models and real-time simulations will be used, so various input device prototypes can be tested rapidly without needing to adapt the instruments and their drives to all the different interfaces. The next step will be to integrate all the modules to demonstrate the feasibility of handheld mechatronic instrument systems and man-machine surgical teams.

ACKNOWLEDGMENT

The authors would like to thank the department of Baden Wuerttemberg for the financial support as well as the students that have contributed to the research.

REFERENCES

[1] Frost & Sullivan. (2013) Image-guided and robot-assisted surgery market in western europe: Market grows despite skepticism over proven advantages of robotics. [Online]. Available: http://www.frost.com/c/10024/sublib/display-report.do?id=M8BC-01-00-00-00

[2] H. W. Schreuder and R. H. Verheijen, "Robotic surgery," *BJOG: An International Journal of Obstetrics & Gynaecology*, vol. 116, no. 2, pp. 198–213, 2009.

[3] H. G. Kenngott, L. Fischer, F. Nickel, J. Rom, J. Rassweiler, and B. P. Müller-Stich, "Status of robotic assistance—a less traumatic and more accurate minimally invasive surgery?" *Langenbeck's Archives of Surgery*, vol. 397, no. 3, pp. 333–341, 2012.

[4] E. O. Olweny, S. L. Best, C. R. Tracy, and J. A. Cadeddu, "New technology and applied research: what the future holds for less and notes," *Archivos españoles de urología*, vol. 65, no. 3, pp. 434–443, 2012.

[5] D. Canes, A. C. Lehman, S. M. Farritor, D. Oleynikov, and M. M. Desai, "The future of notes instrumentation: Flexible robotics and in vivo minirobots," *Journal of endourology / Endourological Society*, vol. 23, no. 5, pp. 787–792, 2009.

[6] A. Balaphas, M. E. Hagen, N. C. Buchs, F. Pugin, F. Volonté, I. Inan, and P. Morel, "Robotic laparoendoscopy single site surgery: a transdisciplinary review," *The International Journal of Medical Robotics and Computer Assisted Surgery*, vol. 9, no. 1, pp. 1–11, 2013.

[7] J. R. Romanelli and D. B. Earle, "Single-port laparoscopic surgery: an overview," *Surgical Endoscopy*, vol. 23, no. 7, pp. 1419–1427, 2009.

[8] J. Rosen, B. Hannaford, C. Richards, and M. Sinanan, "Markov modeling of minimally invasive surgery based on tool/tissue interaction and force/torque signatures for evaluating surgical skills," *IEEE Transactions on Biomedical Engineering*, vol. 48, no. 5, pp. 579–591, 2001.

[9] R. Reilink, S. Stramigioli, A. M. Kappers, and S. Misra, "Evaluation of flexible endoscope steering using haptic guidance," *The International Journal of Medical Robotics and Computer Assisted Surgery*, vol. 7, no. 2, pp. 178–186, 2011.

[10] R. Reilink, A. M. L. Kappers, S. Stramigioli, and S. Misra, "Evaluation of robotically controlled advanced endoscopic instruments," *The International Journal of Medical Robotics and Computer Assisted Surgery*, p. n/a, 2013.