I. INTRODUCTION (SINGLE SITE SURGICAL ROBOT)

In conventional open surgeries, large incisions are often made to allow surgeons full visualization of the targeted surgical site but this is often associated with increased pain, blood loss, possible risk of infection and prolonged hospitalization to the patient [1]. Computer-assisted robotic minimally invasive surgery (MIS) has become increasingly popular over conventional open surgical procedures as it can allow dexterous maneuverability of surgical instruments within the body cavity through small incisions [2]. Typical MIS procedures with existing technologies require multiple small incisions or a single incision for the insertion of surgical instruments [3].

In multi-port systems, more than one incisions are required to insert the laparoscopic instruments, camera and additional auxiliary surgical tool inside the body. The surgeons acclimatize themselves to operate these systems through training, despite inadequate workspace and poor ergonomics (limited space) that makes certain manipulations difficult [4]. As the motors in these systems are externally driven, re-positioning of the laparoscopic instruments during the surgical procedure is difficult and thus require more incisions. In more recent development, the instruments for the da Vinci Xi system (Intuitive Surgical, Inc.) can be repositioned, however, this is for multi-port access only [5].

Single-port robot assisted surgical systems is a technological advancement that enhances the existing benefits of MIS. In these systems, only one incision (usually through the umbilicus) is required to reach the surgical site. Despite potential advantages of single-port systems, several challenges still exist such as poor triangulation of surgical instruments, poor working ergonomics for the insertion of multiple instruments into the abdominal cavity and the inability to apply off-axis forces [6].

Recently, various groups have developed single-site surgical robotic systems, such as the da Vinci Sp system from Intuitive Surgicals Inc., SPORT surgical system from Titan Medical Inc., single-port system from Samsung Advanced Institute of Technology [7,8]. In systems that have external-motor driven arms, the system footprint is usually bulky and it is difficult to reposition the arms, however, torque output is higher as compared to compact systems [9].

The concept of developing miniaturized in-vivo robotic instruments with the state-of-the-art technology and endoscopic navigation has become compelling in recent decades [10]. SPRINT, a 6-dof robotic system, has four in-vivo actuators and shoulder joint operating outside the human body [2]. It consists of two robotic arms (diameter 18 mm). The system is inserted in the abdominal cavity through a cannula of 34 mm diameter. Due to limited in-vivo dof, it is not possible for the surgeon to re-position the robotic arms once they are inserted. In a system designed by Wortman et al., a pair of in-vivo actuated 7-dof robotic arms (diameter 26 mm) has a feature of repositioning by increasing their default incision size (30 mm) [11]. With smaller incision size requirement, the systems possessing snake-like robotic arms designed to work in a confined workspace, however, torque availability is comparatively less [12,13].

The major challenges in single-port surgical systems' design process are to reduce the incision size, enough torque availability at the end-effector and possibility of arms re-positioning without increasing the incision size.

REFERENCES

[1] Camarillo D B, Krummel T M and Salisbury J K 2004 Robotic technology in surgery: Past, present, and future Am. J. Surg. 188 2–15

[2] Quaglia C, Petroni G, Niccolini M, Caccavaro S, Dario P and Menciassi A 2014 Design of a Compact Robotic Manipulator for Single-Port Laparoscopy J. Mech. Des. 136 105001

[3] Ortmaier T, Weiss H and Falk V 2004 Design requirements for a new robot for minimally invasive surgery Ind. Robot An Int. J. 31 493–8

[4] Kazanzides P, Fichtinger G, Hager G D, Okamura A M, Whitcomb L L and Taylor R H 2008 Surgical and interventional robotics - Core concepts, technology, and design IEEE Robot. Autom. Mag. 15 122–30

[5] Wilson T G 2014 Advancement of technology and its impact on urologists: Release of the da Vinci Xi, A new surgical robot Eur. Urol. 66 793–4

[6] Isaac-Lowry O J, Okamoto S, Pedram S A, Woo R and Berkelman P 2017 Compact teleoperated laparoendoscopic single-site robotic surgical system: Kinematics, control, and operation Int. J. Med. Robot. Comput. Assist. Surg. e1811

[7] Beasley R 2012 Medical Robots: Current Systems and Research Directions J. Robot. 2012

[8] Choi H, Kwak H, Lim Y and Kim H 2014 Surgical robot for single-incision laparoscopic surgery IEEE Trans. Biomed. Eng. 61 2458–66

[9] Autorino R, Kaouk J H, Stolzenburg J U, Gill I S, Mottrie A, Tewari A and Cadeddu J A 2013 Current status and future directions of robotic single-site surgery: a systematic review Eur. Urol. 63 266–80

[10] Díaz C E, Fernández R, Armada M and García Gutiérrez F de J 2015 State of the art in robots used in minimally invasive surgeries. Natural Orifice Transluminal Surgery (NOTES) as a particular case Ind. Robot An Int. J. 42 508–32

[11] Wortman T D, Meyer A, Dolghi O, Lehman A C, McCormick R L, Farritor S M and Oleynikov D 2012 Miniature surgical robot for laparoendoscopic single-incision colectomy Surg. Endosc. 26 727–31

[12] Mitchell C R, Hendrick R J, Webster R J III and Herrell S D 2016 Toward Improving Transurethral Prostate Surgery: Development and Initial Experiments with a Prototype Concentric Tube Robotic Platform J. Endourol. 30 692–6

[**13**] Shang J, Leibrandt K, Giataganas P, Vitiello V, Seneci C A, Wisanuvej P, Liu J, Gras G, Clark J, Darzi A and Yang G-Z 2017 A Single-Port Robotic System for Transanal Microsurgery—Design and Validation IEEE Robot. Autom. Lett. 2 1510–7

II. INTRODUCTION (FOR NOTES)

The natural orifice transluminal endoscopic surgery (NOTES) is a step forward in minimizing the patients' trauma due to surgery. This is the advancement in the robot-assisted minimal invasive surgery from multi-port systems and single-port systems [1]. Theoretically, the insertion mechanism of single incision laparoscopic surgery (SILS) and NOTES procedures (for abdomen) should be the same i.e. access through a single opening either from incision on abdomen (generally through navel) or from natural orifice. However, in SILS, robotic arms can be directly deployed to the operating site without any entry constraints unlike in NOTES where pelvic bone structure poses obstacles. Therefore, the workspace requirements for SILS systems are different and less complex as compared to NOTES requirements. Several robotics platforms have been developed for NOTES procedure and can be classified as their natural orifice entry such as trans-nasal, trans-oral, trans-vaginal and trans-anal surgical procedures [2], [3], [4]. However, the objectives and the environmental constraints for these systems were different and their respective work envelop was also not comparable to each other. In this short communication, our focus is on the work envelope of the tele-operated robotic arms inside abdominal cavity and their difficulties to attain certain postures under constrained environment. The first problem encountered by the single port systems is triangulation of robotic arms [5]. The multi-port systems provide better triangulation, however there are another problem of interference of robotic arms and restricted work space which effects the surgeon's ergonomics while operating [6], [7]. A transrectal Micro-IGES system is designed for removal of colorectal cancer from the rectum and the complete work-envelop of the robotic arms is sufficient enough to cover the confined region of rectum. Since, the objective was different and with a very limited work envelop, this system cannot be deployed in abdominal cavity [8]. Similarly, various systems have been reported in the past which highlighted the obstacles posed by the pelvic region bone structure and found difficulty to access the abdominal cavity through natural orifice [9], [10].

III. PROBLEM DEFINITION

In minimal invasive surgeries, single port robotic platform required only one small incision to insert laparoscopic tools inside the abdominal cavity through either cannula or gel-port. A pair of 7-dof robotic arms (each), designed by our group, was successfully utilized in an animal trial for the validation of single port system's feasibility [11]. However, the same platform cannot be used for NOTES due to the obstacles posed by the bone structure of pelvic region.

Fig. 1 shows the bone structure of the pelvic region, obstacles and possible/required robotic arms' postures at the site of surgical procedures. The sacral promontory bone posed major challenge for any robotic surgical system while its insertion through natural orifice (trans-anal or trans-vaginal). There are two scenarios to avoid this bone:

i. Use of cannula to avoid the bone and robotic arms can enter inside the abdominal cavity as shown in Fig. 2.

   Complication: The insertion of cannula is in such a way that robotic arms would face towards abdominal wall (which is approx. 10 cm away after insufflation). At fully stretched state, the robotic arms must avoid to collide with abdominal wall.

ii. Induce flexibility in the robotic arms to avoid the obstacle and reach at the operation site with comparatively good triangulation.

   Complication: More expansion of the arms for better triangulation may cause collision of the elbows with the abdominal side-walls.

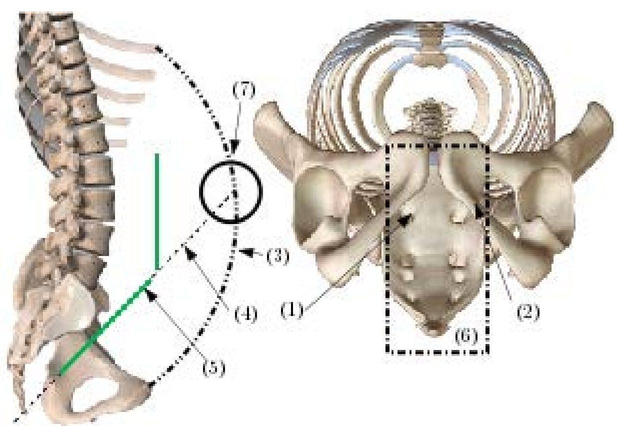

Fig. 1. Problem definition: (1) Sacral promontory (2) Pelvic bone (3) Insufflated abdominal wall (4) Robotic arm facing towards abdominal wall while entering through natural orifice (5) Required posture of robotic arm inside abdominal cavity (6) Natural orifice entry site (7) Possible collision of arms with abdominal while entering.

REFERENCES

[1] S. Micali *et al.*, "New trends in minimally invasive urological surgery. What is beyond the robot?," *World J. Urol.*, vol. 31, no. 3, pp. 505–513, 2013.

[2] M. Remacle, V. M. N. Prasad, G. Lawson, L. Plisson, V. Bachy, and S. Van der Vorst, "Transoral robotic surgery (TORS) with the Medrobotics Flex^{TM} System: first surgical application on humans," *Eur. Arch. Oto-Rhino-Laryngology*,

vol. 272, no. 6, pp. 1451–1455, 2015.

[3] P. J. Schuler *et al.*, “Hybrid procedure for total laryngectomy with a flexible robot-assisted surgical system,” *Int. J. Med. Robot. Comput. Assist. Surg.*, 2017.

[4] J. Burgner *et al.*, “A Telerobotic System for Transnasal Surgery,” *IEEE/ASME Trans. Mechatronics*, vol. 19, no. 3, pp. 996–1006, 2014.

[5] M. Hwang *et al.*, “A single port surgical robot system with novel elbow joint mechanism for high force transmission,” *Int. J. Med. Robot. Comput. Assist. Surg.*, no. June 2016, p. e1808, 2017.

[6] D. Pisla, A. Szilaghyi, C. Vaida, and N. Plitea, “Kinematics and workspace modeling of a new hybrid robot used in minimally invasive surgery,” *Robot. Comput. Integr. Manuf.*, vol. 29, no. 2, pp. 463–474, 2013.

[7] A. A. Thakre, Y. Bailly, L. W. Sun, F. Van Meer, and C. K. Yeung, “Is Smaller Workspace a Limitation for Robot Performance in Laparoscopy?,” *J. Urol.*, vol. 179, no. 3, pp. 1138–1143, 2008.

[8] J. Shang *et al.*, “A Single-Port Robotic System for Transanal Microsurgery—Design and Validation,” *IEEE Robot. Autom. Lett.*, vol. 2, no. 3, pp. 1510–1517, 2017.

[9] P. Wilhelm, S. Axt, P. Storz, S. Wenz, S. Müller, and A. Kirschniak, “Pure Natural Orifice Transluminal Endoscopic Surgery (NOTES) with a new elongated, curved Transanal Endoscopic Operation (TEO) device for rectosigmoid resection: a survival study in a porcine model,” *Tech. Coloproctol.*, vol. 20, no. 5, pp. 273–278, May 2016.

[10] P. Sylla, F. F. Willingham, D. K. Sohn, D. Gee, W. R. Brugge, and D. W. Rattner, “NOTES Rectosigmoid Resection Using Transanal Endoscopic Microsurgery (TEM) with Transgastric Endoscopic Assistance: A Pilot Study in Swine,” *J. Gastrointest. Surg.*, vol. 12, no. 10, p. 1717, Aug. 2008.

[11] K. L. Yung, J. L. K. Cheung, S. W. Chung, S. Singh, and C. K. Yeung, “A Single-Port Robotic Platform for Laparoscopic Surgery with a Large Central Channel for Additional Instrument,” *Ann. Biomed. Eng.*, 2017.

I. **INTRODUCTION (Breast Biopsy Mechanism)**

Worldwide, breast cancer is the most frequently diagnosed cancer and the principal cause of cancer death among women [1], [2]. In order to improve the disease’s survival rate, it is essential to accurately detect cancerous growths in early stages by performing a breast biopsy (which extracts and analyses sample tissues from the suspicious area). This procedure is usually conducted in a minimally-invasive way by introducing a needle into the tissues and guiding it with some imaging modality, such as magnetic resonance imaging (MRI). It has been shown that MRI provides good soft tissue contrast and image resolution, has higher detection rates than ultrasound or mammogram [3], [4], and does not expose the patient to the damaging ionizing radiation of x-rays.

In the current practice of MRI-guided biopsy, the patient is first placed in a prone position with the breast fixed with a special immobilization device commonly referred to as the grid. A first MRI scan is performed to obtain a diagnosis image, which helps physicians to locate the lesion and to calculate the needle’s insertion trajectory. Once the needle is introduced into the tissues, an additional scan is performed to verify its position, which if deviated from its target, further scans and adjustments must be performed, see e.g. [5]–[7]. This repetitive needle positioning process remains up to this day mostly manual. Note that performing multiple adjustments is time-consuming, expensive, and increases the trauma inflicted to the tissues. Therefore, there is a clear need to develop a robotic system which can (semi-)automate the complex insertion process. This is precisely our goal in this paper.

There are several challenges in developing this type of robot. First, the high magnetic field used in MRI restricts the types of materials that can be used to fabricate the robot’s structure; this imaging modality prohibits the use of ferromagnetic metals (e.g. stainless steel). Second, this strong magnetic environment also restricts the types of actuators that can be used to drive the needle’s motion; standard electric motors cannot be placed inside the scanner room since their working principle is based on the electromagnetic effect. Third, in order to avoid degrading the image, special efforts must also be placed to the customization of all mechatronic components and sensors.

In the past decade, many breast biopsy robots have been designed but for ultrasound-guided interventions, see e.g. [8], [9]. The development of robots for MRI interventions has been addressed before by some research groups (for comprehensive reviews, we refer the reader to [10], [11]). In general, these robots are driven by four main actuation methods: distant/remote actuation [12], piezoelectric motors [13], hydraulic actuation [14], and pneumatic actuation [15]. An early work of MRI-guided breast biopsy robots is reported in [16], which presents a 6-DOF needle insertion system driven by piezoelectric motors. In [17] a hydraulic needle driver robot which uses continuous MRI in presented; this single DOF mechanism is tele-operated from a master station outside the scanning room and provides the user with a haptic force feedback. In [18], a needle manipulator actuated with both, pneumatic cylinders and a piezo-motor is presented. Recently, the Centre for Surgical Invention & Innovation developed a robot for breast biopsy and ablation which can operate inside a closed bore scanner [19].

Note that most existing breast biopsy robots (including the above mentioned systems) are too long to be used for lateral needle insertions inside the MRI scanner. The capability to place the robot in a lateral configuration is crucial as most lesions (around 62%) are located in the breast’s outer-upper zone, see [20]. This feature clearly limits the applicability of the above-mentioned breast biopsy robots.

In current scenario, we require the mechatronic design and development of a new robot which can insert the biopsy needle into the tissues while operating inside the scanner's bore; the magnetic compatibility of the proposed pneumatic insertion mechanism allows it to be used even during continuous imaging. Special efforts have been required to optimize the robot's dimension such that it can be used to perform both frontal and lateral insertions inside an MRI scanner.

REFERENCES

[1] A. Jemal, F. Bray, M. Center, J. Ferlay, *et al.*, "Global cancer statistics," *J CA Cancer*, vol. 61, no. 2, pp. 69–90, 2011.

[2] H. Zeng, R. Zheng, S. Zhang, X. Zou, and W. Chen, "Female breast cancer statistics of 2010 in china: estimates based on data from 145 population-based cancer registries," *J Thorac Dis*, vol. 6, no. 5, pp. 466–470, 2014.

MRI-guided breast biopsy," *Am. J. Roentgenol*, vol. 191, no. 6, pp. 1798– 1804, 2008.

[8] V. Mallapragada, N. Sarkar, and T. K. Podder, "Toward a robot-assisted breast intervention system," *IEEE/ASME Tran. Mechatronics*, vol. 16, no. 6, pp. 1011–1020, Dec 2011.

[9] T. R. Nelson, A. Tran, H. Fakourfar, and J. Nebeker, "Positional calibration of an ultrasound image-guided robotic breast biopsy system," *J. Ultrasound Med.*, vol. 31, no. 3, pp. 351–359, 2012.

[10] N. V. Tsekos, A. Khanicheh, E. Christoforou, and C. Mavroidis, "Magnetic resonance-compatible robotic and mechatronics systems for imageguided interventions and rehabilitation: A review study," *Annu. Rev. Biomed. Eng.*, vol. 9, no. 1, pp. 351–387, 2007.

[11] H. Elhawary, Z. Tse, H. Tsz, A. Hamed, *et al.*, "The case for MRcompatible robotics: a review of the state of the art," *Int. J. Med. Rob. Compt. Ass. Surgery*, vol. 4, no. 2, pp. 105–113, 2008.

[12] K. Chinzei and K. Miller, "Towards MRI guided surgical manipulator," *Med. Sci. Monit.*, vol. 7, no. 1, pp. 153–163, 2001.

[13] H. Su, W. Shang, G. A. Cole, G. Li, *et al.*, "Piezoelectrically actuated robotic system for MRI-guided prostate percutaneous therapy," *IEEE/ASME Tran. Mechatronics*, vol. 20, no. 4, pp. 1920–1932, 2015.

[14] R. Gassert, R. Moser, E. Burdet, and H. Bleuler, "MRI/fMRI-compatible robotic system with force feedback for interaction with human motion," *IEEE/ASME Trans. Mechatronics*, vol. 11, no. 2, pp. 216–224, 2006.

[15] D. Stoianovici, A. Patriciu, D. Petrisor, D. Mazilu, and L. Kavoussi, "A new type of motor: Pneumatic step motor," *IEEE/ASME Trans. Mechatronics*, vol. 12, no. 1, pp. 98–106, 2007.

[16] W. A. Kaiser, H. Fischer, J. Vagner, and M. Selig, "Robotic system for biopsy and therapy of breast lesions in a high-field whole-body magnetic resonance tomography unit," *Invest. Radiol.*, vol. 35, no. 8, pp. 513–519, 2000.

[17] R. Kokes, K. Lister, R. Gullapalli, B. Zhang, *et al.*, "Towards a teleoperated needle driver robot with haptic feedback for RFA of breast tumors under continuous MRI," *Med. Image Anal.*, vol. 13, no. 3, pp. 445 – 455, 2009.

[18] B. Yang, S. Roys, U.-X. Tan, M. Philip, *et al.*, "Design, development, and evaluation of a masterslave surgical system for breast biopsy under continuous MRI," *Int. J. Robot. Res.*, vol. 33, no. 4, pp. 616–630, 2014.

[19] K. G. Chan, T. Fielding, and M. Anvari, "An image-guided automated robot for mri breast biopsy," *Int. J. Med. Robot. Comp.*, 2016, rCS-150153.R4.

[20] A. H. Lee, "Why is carcinoma of the breast more frequent in the upper outer quadrant? a case series based on needle core biopsy diagnoses," *The Breast*, vol. 14, no. 2, pp. 151 – 152, 2005.