Perceptual Docking for Robotic Control

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Abstract. In current robotic surgery, dexterity is enhanced by microprocessor controlled mechanical wrists which allow motion scaling for reduced gross hand movements and improved performance of micro-scale tasks. The continuing evolution of the technology, including force feedback and virtual immobilization through real-time motion adaptation, will permit complex procedures such as beating heart surgery to be carried out under a static frame-of-reference. In pursuing more adaptive and intelligent robotic designs, the regulatory, ethical and legal barriers imposed on interventional surgical robots have given rise to the need of a tightly integrated control between the operator and the robot when autonomy is considered. This paper outlines the general concept of *perceptual docking* for robotic control and how it can be used for learning and knowledge acquisition in robotic assisted minimally invasive surgery such that operator specific motor and perceptual/cognitive behaviour is acquired through *in situ* sensing. A gaze contingent framework is presented in this paper as an example to illustrate how saccadic eye movements and ocular vergence can be used for attention selection, recovering 3D tissue deformation and motor channelling during minimally invasive surgical procedures.

Keywords: perceptual docking, minimally invasive surgery, perceptual feedback, eye tracking, machine vision, deformation recovery, 3D tracking, autonomous robot, robotic control, haptics, human-robot interfacing.

1 Introduction

In robotic control, current research is generally carried out under the dichotomy between autonomous and manipulator technologies. Intelligence of the robot is typically pre-acquired through high-level abstraction and environment modelling. With the increasing maturity of master-slave technology in robotic surgery, manual dexterity is enhanced by microprocessor controlled mechanical wrists that allow motion scaling for reduced gross hand movements and improved performance of micro-scale tasks. The continuing evolution of the technology, including force feedback and virtual immobilization through real-time motion adaptation, will permit more complex procedures such as beating heart surgery to be carried out under a static frame-of-reference. The quest for performing ever-complex surgical tasks has given rise to the need of more autonomous control in order to augment the capabilities of the surgeon

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by taking the best from the robot and human. However, the regulatory, ethical and legal barriers imposed on interventional surgical robots dictate the need of a tightly integrated control between the operator and the robot.

It is well recognised that the success of Minimally Invasive Surgery (MIS) is coupled with an increasing demand on surgeons' manual dexterity and visuomotor control due to the complexity of instrument manipulations. Tissue deformation combined with restricted workspace and visibility of an already cluttered environment imposes significant challenges on surgical ergonomics related to surgical precision and safety. With the availability of robotic assisted MIS, existing research has explored the use of motion stabilisation to simplify the execution of delicate surgical tasks such as small vessel anastomosis. The stereoscopic optics provided by systems such as the daVinci (Intuitive Surgical CA), also offer an ideal platform for incorporating computer vision methods for improving surgical workflow through enhanced visualisation.

Although the fine manipulation capabilities of MIS robots in performing scaled down, steady, tremor-free motion are well appreciated, the future clinical impact of the technology relies heavily on machine intelligence of the system and its ability in bridging the sensory information such as tactile feedback between the tool tip and human hands. Recently, the concept of *perceptual docking* has been developed by researchers at Imperial College London, UK for more effective surgical robotic control. The word docking is different in meaning to the conventional term used in mobile robots - it represents a fundamental paradigm shift of perceptual learning and knowledge acquisition for robotic systems in that operator specific motor and perceptual/cognitive behaviour is acquired *in situ* through human-robot interaction. Humans have unexcelled flexibility and hand-eye coordination, as well as finely developed sense of touch. Our vision system is particularly superior in image understanding, feature tracking, 3D perception, morphological registration, and integrating diverse sources of visual cues. Whilst the use of conventional computer vision techniques for 3D structural recovery and registration for intra-operative guidance has encountered major difficulties in the presence of large tissue deformation, there has been very limited work in making effective use of the human vision system for simplifying, as well as augmenting, some of the complex visual processing tasks.

In this paper, we will provide an overview of the research related to *perceptual docking* and outline some example applications of the system for shifting the computational burden towards perceptually enabled channels.

2 Modes of Human-Robot Interface

Although the introduction of the term *perceptual docking* is relatively recent, the basic idea of bridging the sensory information between human and machine has been around for many years. William Grey Walter, who discovered contingent negative variation (CNV) effect - an increasing negative shift of the cortical electrical potentials associated with an anticipated response to an expected stimulus, and created *Machina Speculatrix* (a light seeking robotic tortoise), already contemplated the use of brain waves for machine control nearly 50 years ago. Whilst creating direct neural interface, either one-way or bi-directional, still remains a major research challenge, researchers are increasingly focussed on natural, non-intrusive methods that are practically useful.

In brain-computer interface, there is a large number of input features that can be measured. These include electrical, magnetic, metabolic, chemical, thermal, mechanical responses to brain activity in both frequency and time-domains. The measurement method is mainly determined by the type of input signals to be measured, their location, spatial resolution, the degree of required signal-to-noise-ratio (SNR), and the potential invasiveness involved. Among these, Electroencephalography (EEG) is one of the most researched modalities. Initially it was used for studying auto-regulation and cognitive feedback. Back in the 70s, Jacques Vidal had already demonstrated the use of computer-generated stimulus to visually evoke potentials to control the movement of a cursor through a two-dimensional maze.

There are other methods based on measuring electrical activity like epidural electrodes and electrocorticography (ECoG), but these are generally invasive, requiring electrodes to be inserted into the brain or spine. Chemical activity in the neurons and glia is also a measurable input by using magnetic resonance spectroscopy and invasive probes. It is worth noting that current techniques are mainly geared towards improving the quality of life of the disabled [1-3]. They are still in their infancy and generally not suited for controlling complex tasks.

With the maturity of non-invasive methods, particularly imaging/spectroscopy based techniques, alternative methods such as magnetoencephalography (MEG) are increasingly being used to measure neural activities. Metabolic features can also be used as input channels and they generally rely on measuring changes in blood flow which can be quantified by fMRI [4], PET and more recently NIRS (Near Infrared Spectroscopy). NIRS can measure changes in cortical oxygenation using refraction of light in living tissues with high circulation density [5]. It is non-invasive and relatively inexpensive. For example, Coyle *et al.* [6] demonstrated a fNIRS based brain-computer interface that used motor imagery as a “mindswitch”. A similar application is proposed by Tsubone *et al* [7]. Sitaram *et al.* [8] demonstrated a spelling task via online control of sensorimotor brain areas in a small group of healthy subjects. More recently, Leff *et al.* demonstrated how NIRS could be effectively used to identify cortical activation patterns between novice and experienced surgeons [9-12]. Dynamic topographs of cortical oxyhaemoglobin intensity changes have been used to study prefrontal response to surgical tasks. The prefrontal cortex is known to be vital for acquisition of visuomotor skills, but its role in the attainment of complex technical skills in terms of both perceptual and motor components, remains poorly understood. It has been shown that its response is highly dependent on technical expertise and manifold embedding has been used to depict practice dependent reorganisation of cortical behaviour in surgical novices [11].

Although these studies have provided insight into certain cortical activation patterns in surgical tasks, their practical use in *perceptual docking* for robotic control still remains farfetched. For practical applications, the input channels need to be non-intrusive and can be naturally (or pervasively) integrated into the working environment. In this regard, the use of remote eye-tracking provides a practical way forward.

3 Gaze-Contingent Perceptual Docking

One of the strongest depth cues available to human is the horizontal disparity that exists between the two retinal images. During surgery, the operating surgeons constantly perform saccadic eye movements and fixations which reflect their attention and cognitive visual search strategies. There is a close relationship between the horizontal disparity and depth perception, which varies with the viewing distance. More specifically, as the fixation point moves away from the observer, the horizontal disparity between the two retinal images decreases. In order to extract quantitative information regarding the depth of the fixation point, ocular vergence needs to be measured, thus providing a veridical interpretation of stereoscopic depth. One technique of achieving this is video-oculography. This is a non-intrusive video based approach used to measure the corneal reflection from a fixed infrared light source in relation to the centre of the pupil, which can be mapped to a unique eye gaze direction. The combined tracking of both eyes provides a binocular vergence measure, which in turn can determine the 3D fixation point.

Eye tracking research has a long history in experimental psychology and it provides objective and quantitative evidence of the user's visual and (mostly overt) attention processes. Visual search is the act of searching for a target within a scene and the myriad of visual search tasks performed in surgery is so large that it has become a reactive rather than deliberative process for most common tasks. During visual searches for a defined target there is evidence for both parallel search, with the target being the first and only fixation point, and for sequential search, in which several fixation points are found leading to the target. The intrinsic dynamics of eye movement are complex, and saccadic eye movement is the most important to consider when studying visual search [13]. The modelling of visual search and information seeking behaviour has attracted significant research interests as it is essential for elucidating the idiosyncrasy behind individual search patterns. Currently, there is a widespread use of eye tracking techniques for art, engineering, psychology, cognitive science, behaviour science, human-machine interfacing, ergonomics, market research, and medical imaging. Related to visual information processing, it has been used for devising gaze contingent systems for medical imaging, image communication, virtual reality displays, image analysis, and robotic vision. The reason for its recent, accelerated use beyond psychological laboratory settings is largely due to advances in CMOS sensors and computing technologies, which make the accuracy, robustness, and calibration processes of the eye-tracking device amenable to practical use.

One of the important uses of the eye tracking information is to reveal the underlying cognitive process involved in surgery. The richness of information provided by eye tracking provides both opportunities and challenges to human robot interaction. Current research in gaze contingent perceptual docking is focussed on the use of eye tracking for commanding instrument control. In MIS, this includes simple instrument manoeuvres such as automatic targeting and panning of the laparoscope, and extracting the intention and visual search strategies of the operator for characterising the visual pathways in deploying hand-eye controls. This allows the design of gaze-adapted user interface for intelligent instrument manipulation. Specific research issues

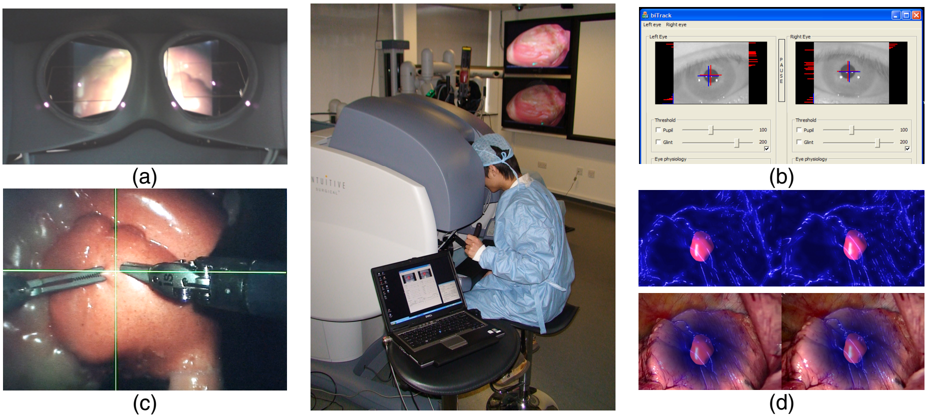

Fig. 1. The experimental setup for the gaze-contingent perceptual docking studies (centre). A binocular eye tracker (a, b, c) is integrated in the daVinci surgical console and a 6-DOF haptic device is used for the experiments. d) Eye tracking is also used for gaze-contingent augmented reality [16].

currently being addressed include how to deal with visual relevance feedback (which in many cases could be implicitly applied), how to deal with overt and covert attention, and how to detect visual saliency and attention. Extensive results have already been generated for using binocular eye tracking for extracting depth from the soft tissue, continuous tracking of tissue deformation [14-15], controlling articulated surgical tools and providing the surgeon with gaze-contingent augmented reality [16]. An example setup of the binocular eye tracking on a daVinci system is shown in Fig. 1.

4 Gaze-Contingent Motor Channelling

Executing dexterous surgical tasks under a static frame of reference for a moving object is one of the ultimate goals of robotic surgery. Current approaches to motion stabilisation are mainly achieved through a mechanical endoscopic stabilizer which provides intracorporeal articulation and facilitates placement of the device to the target vessel. To avoid tools entering unsafe anatomical regions, the concept of active constraints (or virtual fixtures, surgical macros) has been introduced. If the tool approaches a volume of space previously defined to be forbidden, the robot can prevent further motion in that direction. In its early implementation of virtual fixtures, the method only relied on pre-operative registered data and fiducial markers without incorporating force sensors. The surgeon can differentiate between cutting hard or soft tissues via the control instrument. They can also manually define safe regions in order to limit the manipulator movement by directing the tool either perpendicularly or tangentially away from a forbidden boundary. This manipulation constraint was first proposed by Rosenberg [17].

In practice, active constraint is a perceptual overlay of abstract sensory information on a workspace in order to improve the fidelity of the link between the operator and environment. Similar to a ruler guiding a pencil, the idea is to reduce the human sensory workload in performing remote-control tasks. The synergistic use of visual-motor cooperation allows perceptual-motor skills to be combined with the constraints provided by the robot, allowing an accurate and safe operation. In implementations of active constraints to date, the boundaries have always been defined pre-operatively and remained static throughout the operation. To perform dynamic update of the constraints in response to tissue deformation and changing surgical conditions, it requires accurate extraction of 3D structural changes either through intra-operative imaging or biomechanical modelling of the target anatomy.

One of the prerequisites of image guided intervention and introducing active constraints is the correct registration and fusion of the 3D data to the target anatomy. This is difficult in MIS, particularly for cardiac procedures due to the deflation of the lung, insufflation of the chest and application of surgical tools, which all contribute to significant morphological deformation and dynamic changes of the heart. Another significant challenge of beating heart surgery is the destabilization introduced by cardiac and respiratory motion, which severely affects precise tissue-instrument interactions and the execution of complex grafts. Mechanical stabilizers permit off-pump procedures by locally stabilizing the target area while the rest of the heart supports blood circulation. Despite this, residual motion remains, which still complicates delicate tasks such as small vessel anastomosis. These problems are compounded with reduced access to the internal anatomy inherent in MIS, which impose difficulties on target localization.

Based on binocular eye-tracking, we have recently proposed the concept of gaze-contingent motor channelling for augmenting the surgeon's motor abilities in controlling the surgical instruments with the aid of human vision [18]. With this framework, tissue geometry and deformation recovery can be obtained through binocular eye tracking by measuring ocular vergence during robotic assisted MIS. Through the known intrinsic and extrinsic parameters of the calibrated stereo laparoscopic camera, the 3D distance between the surgeon's eye fixation point on the tissue and the laparoscopic instrument can be recovered. By implementing force interactions based on the relative separation between the fixation point and the position of the surgical instrument, there is a strong indication that manipulation of the instrument is enhanced and hand-eye coordination is significantly improved.

Fig. 2a illustrates a haptic-master surgical manipulation station which consists of a stereoscopic console, a binocular eye tracker and two haptic devices used to control the surgical instrument. The exerted attractive forces are based on the separation between the fixation point and the instrument. It has been shown that the amount of improvement achieved in instrument manipulation with and without the use of visual-motor channelling is significant. It is expected that this approach can also benefit many of the existing human-computer interfaces used in tele-presence robot manipulation. As shown in Fig. 2b, a haptic boundary comprising cones and a plate is formed and located on the eye-fixation point on the tissue surface. This is used to confine the instrument working space into a safe region such that the operator is only allowed to approach the deforming tissue (epicardial surface in this example) through the conical pathway defined [18].

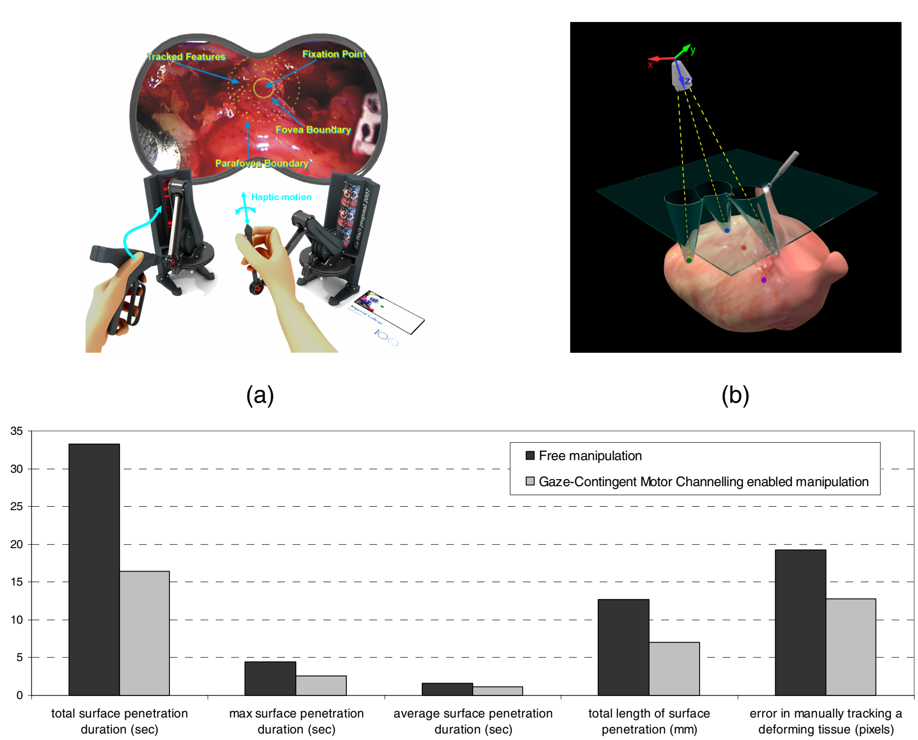

Fig. 2. (a) The conceptual design of a haptic and eye tracking enabled manipulation control station; (b) the conical pathways carved out underneath the safety boundary based on the fixation point of the surgeon; the graph demonstrates the improvement achieved in terms of instrument manipulation during a motor tracking task of a deforming tissue with and without gaze contingent motor channelling

5 Improved Haptics and Perceptual Feedback

In robotic surgery, the use of master-slave technology has created a physical separation between the surgeon and the patient. The use of servo controller also introduces a missing link between the visual and the motor sensory channels. To reconnect the visuomotor sensory feedback, both cutaneous tactile and kinesthetic forces have to be incorporated into the control interfaces. Some early psycho-haptic experiments designed by Okamura *et al.* characterized the problem with the deficiency of haptic feedback in tele-manipulation surgery [19]. Although there is substantial research work on haptic feedback [20-23], this is mainly limited to simulating the force reactions between tissue and surgical instruments. Realistic *in vivo* haptic sensing is difficult to obtain in complicated robot manipulation environments since the instruments are usually interacting with many objects concurrently (*e.g.* trocar, tissue and other tools). Because of this, multiple miniaturised force sensors need to be embedded in the surgical instrument with practical considerations of biocompatibility, sterilization and interactive tactile displays.

Currently, most haptic force feedback devices are limited to generating point forces and torque reaction to the user's hand. Example platforms include the well-known 6 DOF haptic feedback devices, such as the PHANTOM device designed with an articulated joint from SensAble Technologies, and Novint Falcon that incorporates a parallel mechanism. Other platforms include a general purpose 7 DOF haptic device for surgery [24], the magnetic levitation haptic device used for texture sensory perception and haptic rendering [25], and the CyberGrasp haptic system. The latest trend in perceptual feedback is in the introduction of haptic interfaces for portable devices. An emerging concept in haptic research also involves collaborative haptic audio visual environments [26]. For these systems to be practical, the weight of the haptic devices must be reduced and ideally should be made wireless. Significant improvements in bandwidth and latency will facilitate realistic playback of recorded sensation. Haptic data compression schemes that exploit human psychosensory limitations will also help to make bandwidth demands more practical. Currently, high fidelity haptic rendering is an actively pursued research topic [27]. It requires the handling of high frequency updates to reduce instability and interestingly, haptic sensor architecture can also be applied to biometrics for multi factor authentication [28]. In a surgical environment, user profiles can be retrieved so that the robot can adapt to the specific behaviour or preference of the operator [29].

In terms of perceptual feedback, another important research challenge is in the provision of high-fidelity augmented reality by effectively combining pre- and intra-operative data such that one can see beyond the exposed tissue surface. This also entails accurate modelling and simulation of soft tissue combined with direct *in vivo, in situ* sensing and imaging. Current research has already made significant in roads into real-time AR systems and the development of *in situ* tissue characterisation techniques based on multi-excitation, multi-spectral imaging to permit simultaneous morphological and functional mapping. It also permits multi-scale image integration such that the visual perceptual capability of the surgeon is significantly enhanced.

6 Conclusions

Empowering robots with human intelligence represents one of the ultimate goals of robotic research. The regulatory, ethical and legal barriers imposed on interventional surgical robots give rise to the need of a tightly integrated control between the operator and robot when autonomy is pursued. The concept of *perceptual docking* represents a new way of knowledge acquisition for robotic systems by using *in situ* learning of operator specific motor and perceptual/cognitive behaviour. In robotic surgery, the technology has developed to a stage that improved motion stabilisation, intra-operative guidance, and active constraints need to be deployed to ensure operating accuracy and consistency. The use of *perceptual docking* naturally avoids some of the major technical hurdles of existing approaches and the technique is also expected to benefit other applications of robotic control beyond surgery.

References

1. Moore, M.M.: Real-World Applications for Brain-Computer Interface Technology. IEEE Trans. on Neural Systems and Rehabilitation Engineering 11(2), 162–165 (2003)
2. Wolpaw, J.R., McFarland, D.J.: Control of a Two-Dimensional Movement Signal by a Noninvasive Brain-Computer Interface in Humans. NeuroScience 101(51), 17849–17854 (2004)
3. Serruya, M.D., Hatsopoulos, N.G., Paninski, L., Fellow, M.R., Donoghue, J.P.: Instant Neural Control of a Movement Signal. Nature 416, 141–142 (2002)
4. Yoo, S.S., Fairneny, T., Chen, N.K., Choo, S.E., Panych, L.P., Park, H., Lee, S.Y., Jolesz, F.A.: Brain-Computer Interface Using fMRI: Spatial Navigation by Thoughts. Neuroreport 15(10), 1591–1595 (2004)
5. Franceschini, M.A., Boas, D.A.: Noninvasive Measurement of Neuronal Activity with Near-Infrared Optical Imaging. NeuroImage 21(1), 372–386 (2004)
6. Coyle, S.M., Ward, T.E., Markham, C.M.: Brain-Computer Interface Using a Simplified Functional Near-Infrared Spectroscopy System. Journal of Neural Eng. 4(3), 219–226 (2007)
7. Tsubone, T., Muroga, T., Wada, Y.: Application to Robot Control Using Brain Function Measurement by Near-Infrared Spectroscopy. In: Proc. of IEEE Eng. Med. Biol. Soc., pp. 5324–5345 (2007)
8. Sitaram, R., Zhang, H., Guan, C., Thulasidas, M., Hoshi, Y., Ishikawa, A., Shimizu, K., Birbaumer, N.: Temporal Classification of Multichannel Near-Infrared Spectroscopy Signals of Motor Imagery for Developing a Brain-Computer Interface. Neuroimage 34(4), 1416–1427 (2007)
9. Leff, D., Koh, P.H., Aggarwal, R., Leong, J., Deligiani, F., Elwell, C., Delpy, D.T., Darzi, A., Yang, G.Z.: Optical Mapping of the Frontal Cortex During a Surgical Knot-Tying Task, a Feasibility Study. In: Medical Imaging Augmented Reality, pp. 140–147 (2006)
10. Leff, D.R., Leong, J.J., Aggarwal, R., Yang, G.Z., Darzi, A.: Could Variations in Technical Skills Acquisition in Surgery be Explained by Differences in Cortical Plasticity? Annals of Surgery 247(3), 540–543 (2008)
11. Leff, D.R., Orihuela-Espina, F., Atallah, L., Darzi, A., Yang, G.Z.: Functional Near Infrared Spectroscopy in Novice and Expert Surgeons - a Manifold Embedding Approach. In: Ayache, N., Ourselin, S., Maeder, A. (eds.) MICCAI 2007, Part II. LNCS, vol. 4792, pp. 270–277. Springer, Heidelberg (2007)
12. Leff, D.R., Elwell, C.E., Orihuela-Espina, F., Atallah, L., Delpy, D.T., Darzi, A.W., Yang, G.Z.: Changes in Prefrontal Cortical Behaviour Depend Upon Familiarity on a Bimanual Co-Ordination Task: an fNIRS Study. Neuroimage 39(2), 805–813 (2008)
13. Yang, G.Z., Dempere-Marco, L., Hu, X.-P., Rowe, A.: Visual Search: Psychophysical Models and Practical Applications. Image and Vision Computing 20, 291–305 (2002)
14. Mylonas, G.P., Darzi, A., Yang, G.Z.: Gaze Contingent Depth Recovery and Motion Stabilisation for Minimally Invasive Robotic Surgery. In: Yang, G.-Z., Jiang, T. (eds.) MIAR 2004. LNCS, vol. 3150, pp. 311–319. Springer, Heidelberg (2004)
15. Mylonas, G.P., Stoyanov, D., Deligianni, F., Darzi, A., Yang, G.-Z.: Gaze-Contingent Soft Tissue Deformation Tracking for Minimally Invasive Robotic Surgery. In: Duncan, J.S., Gerig, G. (eds.) MICCAI 2005. LNCS, vol. 3749, pp. 843–850. Springer, Heidelberg (2005)
16. Lerotic, M., Chung, A.J., Mylonas, G., Yang, G.-Z.: pq-Space Based Non-Photorealistic Rendering for Augmented Reality. In: Ayache, N., Ourselin, S., Maeder, A. (eds.) MICCAI 2007, Part II. LNCS, vol. 4792, pp. 102–109. Springer, Heidelberg (2007)

17. Rosenberg, L.B.: Virtual Fixtures: Perceptual Tools for Telerobotic Manipulation. In: Proc. of the IEEE Annual International Symposium on Virtual Reality, pp. 76–82 (1993)
18. Mylonas, G.P., Kwok, K.-W., Darzi, A., Yang, G.Z.: Gaze-Contingent Motor Channelling and Haptic Constraints for Minimally Invasive Robotic Surgery. In: Proceedings of the 11th International Conference on Medical Image Computing and Computer Assisted Intervention, MICCAI 2008, New York (to appear, 2008)
19. Okamura, A.M.: Methods for Haptic Feedback in Teleoperated Robot-Assisted Surgery. Industrial Robot: An International Journal 31(6), 499–508 (2004)
20. Mendoza, C., Laugier, C.: Tissue Cutting Using Finite Elements and Force Feedback. In: Proc. of International Symposium on Surgery Simulation and Soft Tissue Modeling, pp. 175–182 (2003)
21. Crouch, J.R., Schneider, C.M., Wainer, J., Okamura, A.M.: A Velocity-Dependent Model for Needle Insertion in Soft Tissue. In: Duncan, J.S., Gerig, G. (eds.) MICCAI 2005. LNCS, vol. 3750, pp. 624–632. Springer, Heidelberg (2005)
22. Heverly, M., Dupont, P., Triedman, J.: Trajectory Optimization for Dynamic Needle Insertion. In: Proc. of the 2005 IEEE International Conf. on Robotics and Automation, pp. 1646–1651 (2005)
23. Kennedy, C.W., Hu, T., Desai, J.P., Wechsler, A.S., Kresh, J.Y.: A Novel Approach to Robotic Cardiac Surgery Using Haptics and Vision. Cardiovascular Engineering: An International Journal 2(1), 15–21 (2002)
24. Tholey, G., Desai, J.P.: A General Purpose 7 DOF Haptic Device: Applications Towards Robot-Assisted Surgery. IEEE/ASME Trans. on Mechatronics 12(6), 662–669 (2007)
25. Unger, B., Hollis, R., Klatzky, R.: JND Analysis of Texture Roughness Perception Using a Magnetic Levitation Haptic Device. In: Proc. Of the 2nd Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, pp. 9–15 (2007)
26. Saddik, E.: The Potential of Haptics Technologies. IEEE Instrumentation and Measurement Magazine 10(1), 10–17 (2007)
27. Lin, M., Salisbury, K.: Haptic Rendering-Beyond Visual Computing. IEEE Computer Graphics and Applications 24(2), 22–23 (2004)
28. Orozco, M., Asfaw, Y., Shirmohammadi, S.S., Adler, A., Saddik, A.E.: Haptic-Based Biometrics: A Feasibility Study. In: Proc. of the Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, pp. 265–271 (2006)
29. Tsagarakis, N.G., Petrone, M., Testi, D., Mayoral, R., Zannoni, C., Viceconti, M., Clapworthy, G.J., Gray, J.O., Caldwell, D.G.: Pre-Operative Planning for Total Hip Arthroplasty Using a Haptic Enabled Multimodal Interface and Framework. IEEE Trans. of Multimedia and Visualization: Special issue in Haptics 13(3), 40–48 (2006)