The International Journal of **Medical Robotics** and **Computer Assisted Surgery**

THE INTERNATIONAL JOURNAL OF MEDICAL ROBOTICS AND COMPUTER ASSISTED SURGERY
Int J Med Robotics Comput Assist Surg 2012; **8**: 127–145.
Published online 9 January 2012 in Wiley Online Library (wileyonlinelibrary.com) **DOI:** 10.1002/rcs.453

REVIEW ARTICLE

Kinematic design considerations for minimally invasive surgical robots: an overview

Chin-Hsing Kuo[1]*
Jian S. Dai[2]
Prokar Dasgupta[3]

[1]*Department of Mechanical Engineering, National Taiwan University of Science and Technology, 43, Sec. 4, Keelung Rd., Taipei 106, Taiwan*

[2]*Centre for Robotics Research, King's College London, Strand, London WC2R 2LS, UK*

[3]*Department of Urology, Guy's and St Thomas' Hospitals NHS Foundation Trust, Guy's Hospital, St. Thomas Street, London SE1 9RT, UK*

*Correspondence to: C.-H. Kuo, Department of Mechanical Engineering, National Taiwan University of Science and Technology, 43, Sec. 4, Keelung Rd., Taipei 106, Taiwan.
E-mail: chkuo717@mail.ntust.edu.tw

Accepted: 7 November 2011

Abstract

Background Kinematic design is a predominant phase in the design of robotic manipulators for minimally invasive surgery (MIS). However, an extensive overview of the kinematic design issues for MIS robots is not yet available to both mechanisms and robotics communities.

Methods Hundreds of archival reports and articles on robotic systems for MIS are reviewed and studied. In particular, the kinematic design considerations and mechanism development described in the literature for existing robots are focused on.

Results The general kinematic design goals, design requirements, and design preferences for MIS robots are defined. An MIS-specialized mechanism, namely the *remote center-of-motion* (RCM) mechanism, is revisited and studied. Accordingly, based on the RCM mechanism types, a classification for MIS robots is provided. A comparison between eight different RCM types is given. Finally, several open challenges for the kinematic design of MIS robotic manipulators are discussed.

Conclusions This work provides a detailed survey of the kinematic design of MIS robots, addresses the research opportunity in MIS robots for kinematicians, and clarifies the kinematic point of view to MIS robots as a reference for the medical community. Copyright © 2012 John Wiley & Sons, Ltd.

Keywords robotic surgery; computer-integrated surgery; medical devices; medical robots; surgical robots; remote center-of-motion; mechanism design

Introduction

Minimally invasive surgery (MIS) is a type of surgery whereby the surgical operation is done through small incisions. The basic operation concept of MIS is to insert the surgical instrument, e.g., the laparoscope, endoscopic camera, percutaneous needle, etc., into the patient's body through a small entry port so that the surgical operation can be implemented inside the patient's body at the instrument tip. In order to enhance the precision and dexterity of MIS operation, modern robotic technology was introduced into the operating room (OR) as early as in 1985, when a standard industrial robot was used in minimally invasive neurosurgery (1). With more than two-decade advance, today many special-purpose surgical robots have been developed to fulfill various requirements in the MIS environment.

A *surgical robot*, according to the definition in (2), is a self-standing console or an element of a larger robotic system designed to assist a surgeon in carrying out a surgical procedure that may include preoperative planning, intraoperative registration to presurgical plans, use of a combination of robotic assist and manually controlled tools for carrying out the plan, and postoperative verification and follow-up. A *minimally invasive surgical robot* may be an active, passive or co-manipulated robot working near the patient, and is either hand- or computer-controlled to maneuver the surgical instrument(s) executing the intraoperative MIS task inside the patient's body. Recently, minimally invasive surgical robots have even been shifted into a non-invasive level, at which the entire embodiment of the robot can be delivered into the patient's body without any incision.

Kinematic design is a predominant phase in the design of MIS robotic manipulators. In this phase, we need to transform a batch of common and vital MIS concerns, e.g. safety, accuracy, ergonomics, and dexterity, into several deliberating kinematic design considerations, e.g. the mechanism topology, workspace, isotropy, etc. to satisfy the surgical requirements. In their own right, these kinematic design considerations will constitute a set of exclusive mechanism and kinematic design challenges for MIS robots. Although these kinematic design considerations are obviously important for MIS robot design, a comprehensive review and discussion about them is still anticipated in both mechanisms and robotics communities.

Therefore, the purpose of this paper is to provide a comprehensive overview of the kinematic design considerations and mechanism development of the robotic manipulators applied for minimally invasive surgery. It should be noted that in this paper we consider only the traditional MIS that has tool motion constraints imposed by the 'minimally invasive' incision. Those special MIS operations that do not require 'small entry' are not considered 'minimally invasive' surgery here. For example, in neurosurgery, if the surgical operation needs to remove a relatively large part of the skull but can carry out the intraoperative therapy without destroying brain tissue, we will not consider it as a general MIS. On the other hand, if the MIS robot is based on the master-and-slave concept, the patient-side manipulator is our major concern, while the surgeon-side console is not considered in this discussion. Furthermore, those robots that use 'non-invasive' techniques, e.g., the natural orifice translumenal endoscopic surgical (NOTES) robots and the autonomous miniaturized surgical robots are outside the scope of this paper.

It should be noted that although different types of minimally invasive surgeries may require different motions for their surgical tools, here we consider the tool motion in laparoscopic surgery as the general case of common MIS. In laparoscopic surgery, the surgical tool requires a four-degree-of-freedom (DOF) motion, including three rotational and one translational ones. In many other types of MIS therapies, however, the required tool motions are a subset of the four DOFs realized in laparoscopic surgery. Therefore, in order to formulate general kinematic design considerations for common MIS robots, here we treat the tool motion in laparoscopic surgery as the most general case. A more detailed explanation of this generalization will be given later.

Based on a review of the literature and systems developed for robotically-assisted minimally invasive surgery, this paper aims to formulate the common kinematic design goals, design requirements, and design preferences for general MIS robots. It also tries to determine the current limitations and open problems in terms of kinematic design for MIS robotic manipulators.

The content of this paper is organized as follows. First, based on the motion analysis of general MIS, the kinematic constraints required by MIS robots are identified. A number of fundamental design issues for robotically-assisted MIS are discussed, from which the pertinent kinematic design tasks are summarized. These kinematic design tasks are then transformed into a complete list of kinematic design goals, design requirements, and design preferences for MIS robots. Next, a special mechanism, namely the 'remote center-of-motion (RCM) mechanism', which is used to overcome the common kinematic challenges in MIS robots, is thoughtfully studied. Based on the RCM mechanism types, a classification for MIS robots is then suggested. Finally, several relevant kinematic properties revealed in MIS robots are compared and discussed.

Materials and Methods

Motion constraints for MIS robots

The task for a surgical robot is basically to assist the surgeon performing surgical movements during surgery. In MIS, the motion requirements include two essential issues. First, the robot needs to manipulate the surgical tool, performing a pivoting 4-DOF motion. Second, the mechanical links and joints of the robotic manipulator should not collide with the patient's body during surgery. These two issues are detailed as follows.

Manipulation mobility

Generally, an MIS surgical instrument is formed as a long and narrow tube and is operated by the surgeon's hand in traditional MIS or by a robotic manipulator in robotically-assisted MIS. The surgical instrument is then manipulated to penetrate the patient's body through a small incision (in certain situations with the assistance of a medical instrument called *trocar*) to carry out surgical operations such as cutting, suturing, tying, etc. at the instrument tip inside the patient's body. Occasionally, a minimally invasive therapy requires several incisions to allow the use of multiple instruments to cooperatively perform the surgical procedure. For example, traditional laparoscopic surgery needs three incisions, one for delivering the *in vivo* camera and the others for accommodating the two laparoscopes.

It can be seen that with such an arrangement the patient's body naturally constitutes a motion constraint to the surgical instrument. The lateral motion of the instrument is confined by the limited small spatial volume at the entry point on the patient's body. Practically, this limited volume is extremely small compared with the surgical instrument. Hence, it is normally considered a

DOI: 10.1002/rcs

point to facilitate the kinematic design process for an MIS device or robot. This arrangement thus constitutes a 'fulcrum effect' at the entry point. The instrument, therefore, can have only four DOFs for manipulation, i.e., pan–tilt–spin rotation (or so-called roll–pitch–yaw motion in kinematics) centered at the entry point for angular orientation and axial translation for depth of penetration (Figure 1).

As introduced above, the motion DOFs of an MIS tool are described by (1) insertion length along the tool spindle axis, (2) tilt and pan angles about the pivoting point, and (3) spin angle about the tool spindle axis. Hence, it would be more convenient to represent the movement of the tool by means of the above four displacements to help the kinematic design and to simplify the control strategy for the robot. This special coordinated displacement is depicted in Figure 2. In this figure, $P(x, y, z)$ is a reference coordinate system attached to the pivoting point whose origin is coincident with the pivoting point P, and $E(u, v, w)$ is a reference coordinate system attached to the end-effector where the w-axis passes through pivoting point P. Due to the pivoting kinematic constraint, the w-axis will always pass through point P wherever the end-effector is displaced.

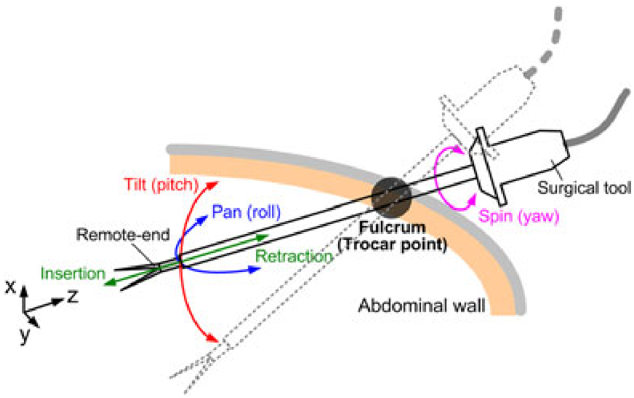

Figure 1. The four degrees of freedom of motion for an MIS instrument

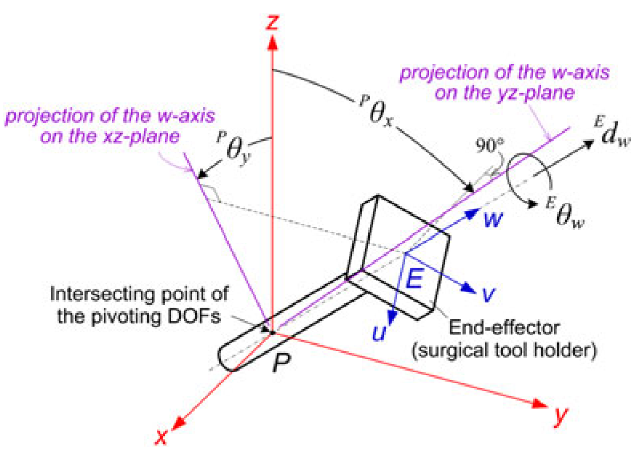

Figure 2. Four practical DOFs used in an MIS instrument

Accordingly, the motion DOFs of the surgical tool are described by four variables, ${}^{P}\theta_x$, ${}^{P}\theta_y$, ${}^{E}\theta_w$, and ${}^{E}d_w$, in which ${}^{P}\theta_x$ and ${}^{P}\theta_y$ imply rotations about the x- and y-axes of coordinate system P, respectively, and ${}^{E}\theta_w$ and ${}^{E}d_w$ imply rotation/translation about/along the w-axis of coordinate system E. Note that superscripts P and E indicate the referencing coordinate in which the rotation/translation is expressed and subscripts x, y and w represent the axis about/along which the end-effector rotates/moves.

It should be noted that although the four DOFs specified above are sufficient to deal with general MIS operations, they are not all required in some MIS applications. For example, while a laparoscopic surgery requires three rotational DOFs for orientating and one translational DOF for inserting the laparoscope about/along the trocar point, a percutaneous needle insertion requires only two rotational DOFs for orientating and one translational DOF for inserting the needle about/along the skin entry point. In this paper, however, we adopt the four DOFs of laparoscopic surgery as the general tool motion in common MIS operations. This generalization is helpful when discussing the general kinematic design considerations for MIS robots.

Extracorporeal workspace volume

In addition to the pivoting 4-DOF motion, a robotically-assisted MIS has also the feature of extracorporeal working volume for the robot. To avoid physical interference between the robot and the patient's body, an MIS robot, which delivers the surgical tool through a small incision on the patient's body, should work *outside* the patient's body. Each movable mechanical link of the robot (except for the surgical tool and its associated instrumentation on the robot) must move freely in OR but cannot touch the patient during surgery. This therefore introduces another vital motion requirement into robot manipulator design, that is, the manipulator should be so well-structured that no interference will occur between the robot and the patient within the motion range of the surgical operation. Meanwhile, the extracorporeal manipulator should control the surgical instrument performing the pivoted motion at the entry point, which should locate outside the manipulator's working volume and is better some distance away from the embodiment of the manipulator.

General surgical issues for MIS robots

In contrast to industrial robots, surgical robots are highly human-interactive robots, so that human factors must be taken into account when designing the robotic manipulator. In effect, some basic surgical issues are necessary and even critical when evaluating the performance of MIS robots. As mentioned above, since an MIS robot is a special-purpose robot, its design specifications will be varied case-by-case when different surgical types or targeted anatomy is applied (even if several systems have been developed for tackling a large range of surgical indications, their applications are still limited to certain domains only, i.e., there is no system that can cope with all kinds of MIS therapies). Within these case-oriented design concerns, however, several common design requirements that are valid in most robotically-assisted MIS can still be concluded. In what follows, we will discuss these general issues in detail. Emphasis will be focused on the associated problems in kinematic design of the robots. Accordingly, a number of design goals (DG) for kinematic design of general MIS robots will be summarized.

Safety

DG1. Kinematic constraint at the entry point.

DG2. Collision-free workspace between the manipulator, surgeon and patient.

DG3. Decoupled rotational and translational degrees of freedom for the surgical instrument.

Safety is the uppermost concern in robotic application for surgery. When designing a surgical robot, the safety issue is involved in multi-stages with various topics such as sterilization, inflection control, sensing and programming, etc. A number of safety issues for medical robots, in either software or hardware perspective, have been discussed by Davies (3) and Fei *et al*. (4)

In terms of kinematic design for MIS robots, three basic design goals concerning safety can be realized. The first two design goals, DG1 and DG2, arise directly from the motion constraints of the MIS robots. To produce the kinematic constraint at the entry point, the robotic manipulator should be properly configured so that all the rotational DOFs of the end-effector can converge at a fixed point and the translational DOF can point in the direction along which the instrument is being inserted/retracted. As to the collision-free problem, a pure extracorporeal mechanism, whose kinematic links and joints (except for the intra-body working part) never touch the patient's body during the whole cycle of motion, will be the best candidate to overcome safety concerns. Further, a safer robot manipulator will be one which minimizes the overall mechanical motion of the manipulator to accomplish the desired motion of the instrument tip (5).

On the other hand, the third design goal, DG3, suggests that a safer MIS robot will be one in which the rotational and translational degrees of freedom of instrument motion are decoupled at the port of entry into the patient (2,6). When the translational DOF of the surgical tool is decoupled from the rotational DOFs, it permits translational actuators to be disabled (or omitted) if only pivoting rotation is needed. In addition, when all or part of the DOFs associated with the trocar point are decoupled, it allows the actuators to be sized to produce the desired rates of motion in the corresponding decoupled degrees of freedom. Furthermore, the decoupled kinematics can provide more rapid manual positioning of the entire mechanism or of selected degrees of freedom by means of manually actuated clutches (6) or back-drivable transmission (7). Consequently, system control and some safety checking can be effectively simplified.

Accuracy

DG4. Output displacement/input displacement ratio.

Accuracy is undoubtedly one of the major design requirements for most robotic applications. In fact, it is much more crucial for surgical robots since any unsatisfied or unexpected position errors might cause unredeemable hazards to the patient or surgeon.

Broadly speaking, the high accuracy of a surgical robot can be achieved in several ways, e.g., tolerance sensitivity, feedback control, manufacturing precision, etc. In kinematic design phase, the kinematic accuracy of an MIS robot depends mainly on the manipulator topology and dimensions. To quantify the kinematic *inaccuracy* in an MIS robot, it has been suggested (8) that the accuracy measure may refer to the ability of the end-effector to achieve maximum displacement (including three-directional translations and three-directional rotations) at its instrument tip based on the minimum displacement of joint spaces. Therefore, the smaller value the output/input displacement ratio has, the better kinematic accuracy the robot possesses. Accordingly, the corresponding design goal can be stated as DG4 above.

However, we should notice that while the output/input displacement ratio is decreased, the extracorporeal workspace volume of the robotic arm may become larger. This could unfortunately reduce the confidence of safety when pursuing a minimal extracorporeal workspace, even a collision-free workspace, for MIS robots. This kind of trade-off between safety confidence and kinematic accuracy should be negotiated carefully when designing an MIS robot. To avoid this, a possible solution may be the use of gearbox transmission, which ensures a high input/output reduction ratio for increased accuracy without any decrease in tool workspace. In summary, whatever the mechanism types are used, the minimum requirement of a satisfactory design should be that the accuracy measure can be as small as possible provided that a collision-free workspace is guaranteed.

Ergonomics

DG5. Inverse of hand-eye coordination.

DG6. Rotational ability of the end-effector.

Ergonomics is a science that has to do with the design of machines and tools that optimize the performance of the user, taking into account the limits of the user (9,10). The ergonomic problems for MIS includes a broad range of concerns, which can be categorized as visualization, manipulation, surgeon posture, mental and physical workload, and the OR environment ergonomics (9). When designing an MIS robot, these topics are spread into many different stages, for example, video set-up, manipulator design, haptic system, etc. throughout the preoperative, intraoperative, and postoperative interventions.

In kinematic design phase, ergonomic concern for MIS robots belongs to the manipulation ergonomics. For a robotically-assisted MIS, the surgical tool is held by either the robotic arm (in master–slave robots or active robots) or the surgeon's hand (in a passive surgical tool

DOI: 10.1002/rcs

holder) at the end of the extra-body. Owing to the 'fulcrum effect' at the tool entry point, the directional movement of the robotic arm or the surgeon's hand reflects an opposite movement of the instrument tip in the patient's body, creating an inversion between visual realization and perceptual manipulation. Currently, this problem is overcome via control rectification in most MIS robots, where the coordinate system is mirrored from the instrument tip to the holding part of the surgical tool. However, a direct solution from the viewpoint of manipulator structure design would be an interesting problem for kinematicans.

On the other hand, as the MIS instrument is held by surgeon's hand in traditional hands-on surgery, manual manipulation will induce ergonomic problems in terms of excessive flexion, supination, and ulnar deviation of the surgeon's wrist (10). This could also be reflected in MIS robots while its manipulator has an unfavorable rotational ability (i.e., the insufficient rotational DOFs, limited angles, and improper singularity of the end-effector). For example, a small tilt angle of the instrument inside the patient's body might lead to an over-rotated angle of the end-effector. For example, two target angles of the instrument might be not reachable from one to the other since they could be located in two different mechanism branches. Therefore, the rotational ability of the end-effector should be considered as an important performance index when designing the robotic manipulator for MIS applications.

Dexterity

DG7. Hand tremor reduction.

DG8. Surgical movement scaling.

One of the most significant advantages of introducing robotics to MIS is that the dexterity (11,12) of traditional surgical operations can be dramatically augmented. The surgical dexterity can be enhanced by robotic systems by improving two major limitations in traditional operations: Hand tremor reduction and surgical movement scaling (13). These two factors have been pushing surgical operations towards a much more precise microsurgical scale.

In current MIS robots, the validation of hand tremor reduction and surgical movement scaling are undertaken with the help of the computer-controlled system (major) and the match-up of manipulator dimensioning (minor). In kinematic design phase, the robot needs to be dimensionally synthesized by taking account of a suitable scaling ratio of the instrument motion with respect to the end-effector or actuation motion. Based on different design requirements, a suitable scaling ratio will be evaluated from different points of view. From the viewpoint of accuracy, for example, an MIS robot will be expected to have a (kinematic) scaling ratio (instrument tip displacement/input displacement) as small as possible.

Kinematic design considerations

In the previous section we specified eight design goals for the kinematic design of MIS robots. In this section, we explain how these design goals can be mapped onto practical kinematic design scenarios. A number of kinematic design requirements and preferences for MIS robots will be proposed and summarized.

Tool motion representation

Figure 2 has indicated that the motion of an MIS instrument is conventionally represented by four displacements, ${}^{P}\theta_x$, ${}^{P}\theta_y$, ${}^{E}\theta_w$, and ${}^{E}d_w$. Therefore, it would be more convenient if the location of the surgical tool could be related to four geometric parameters that correspond to the four motion displacements, respectively.

Figure 3, for example, provides one way to achieve this goal. In this figure, the location of the surgical tool, i.e., $E(u, v, w)$, is described by three projective angular displacements (${}^{w}\theta_{xz}$, ${}^{w}\theta_{yz}$, θ_w) and one linear displacement d_w. Let $\mathbf{w} = [w_x, w_y, w_z]^{\mathrm{T}}$ be the unit vector pointing along the w-axis. As shown in the figure, $\mathbf{w}'_{yz}$ is the projection of vector $\mathbf{w}$ on the yz-plane and $\mathbf{w}'_{xz}$ is the projection of vector $\mathbf{w}$ on the xz-plane. Accordingly, the pan angle ${}^{w}\theta_{yz}$ of $E(u, v, w)$ can be measured from the positive z-axis to $\mathbf{w}'_{yz}$ by rotating about the negative x-axis, and the tilt angle ${}^{w}\theta_{xz}$ of $E(u, v, w)$ can be measured from the positive z-axis to $\mathbf{w}'_{xz}$ by rotating about the positive y-axis. On the other hand, let $\mathbf{a} = [a_x, a_y, a_z]^{\mathrm{T}}$ be an arbitrary vector passing through the origin of coordinate system xyz and $\mathbf{a}'$ be the projective unit vector of $\mathbf{a}$ on the uv-plane. Therefore, the spin angle θ_w of $E(u, v, w)$ could be defined as the angle measured from $\mathbf{a}'$ to the v-axis by rotating about the positive w-axis. Accordingly, the orientation of coordinate system $E(u, v, w)$ with respect to coordinate system $P(x, y, z)$ is completely described by the three angular parameters, ${}^{w}\theta_{yz}$, ${}^{w}\theta_{xz}$, and θ_w, as

$$\mathbf{w} = \left[\zeta \tan {}^{w}\theta_{yz}, \zeta \tan {}^{w}\theta_{xz}, \zeta\right]^{\mathrm{T}}, \tag{1}$$

$$\mathbf{u} = \mathbf{A}\mathbf{a}', \tag{2}$$

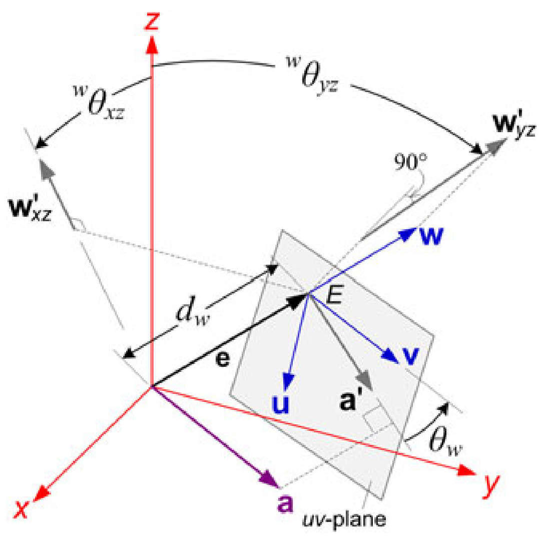

Figure 3. A projective representation for expressing the location of the surgical instrument

DOI: 10.1002/rcs

$$\mathbf{v} = \mathbf{w} \times \mathbf{u} \tag{3}$$

where

$$\zeta = \begin{cases} +1/\sqrt{1+\tan^2({}^{w}\theta_{yz})+\tan^2({}^{w}\theta_{xz})}, & \text{when} \quad -\pi/2 \leq {}^{w}\theta_{yz} \leq \pi/2 \\ -1/\sqrt{1+\tan^2({}^{w}\theta_{yz})+\tan^2({}^{w}\theta_{xz})}, & \text{otherwise,} \end{cases}$$

$$\mathbf{A} = \begin{bmatrix} c\theta_w + w_x^2(1-c\theta_w) & w_x w_y(1-c\theta_w) - w_z s\theta_w & w_x w_z(1-c\theta_w) + w_y s\theta_w \\ w_y w_z(1-c\theta_w) + w_z s\theta_w & c\theta_w + w_y^2(1-c\theta_w) & w_y w_z(1-c\theta_w) - w_x s\theta_w \\ w_z w_x(1-c\theta_w) - w_y s\theta_w & w_z w_y(1-c\theta_w) + w_x s\theta_w & c\theta_w + w_z^2(1-c\theta_w) \end{bmatrix},$$

$$\mathbf{a}' = \mathbf{a} - (\mathbf{a}\cdot\mathbf{w})\mathbf{w} = \begin{bmatrix} a_x - (a_x w_x + a_y w_y + a_z w_z)w_x \\ a_y - (a_x w_x + a_y w_y + a_z w_z)w_y \\ a_z - (a_x w_x + a_y w_y + a_z w_z)w_z \end{bmatrix}.$$

Note that $-\pi \leq {}^{w}\theta_{yz}, {}^{w}\theta_{xz} \leq \pi$ and rotation matrix **A** is derived from the Rodrigues' rotation formula† (14,15) in which $c\theta_w$ is a shorthand for $\cos\theta_w$ and $s\theta_w$ for $\sin\theta_w$. Vector **a** can be specifically selected for helping define the spin angle θ_w in a more convenient way. For example, it may be chosen as the unit vector of the x-axis, the unit vector of the y-axis, or the projected vector of the w-axis on the xy-plane, etc. After vector **w** is obtained, the position of $E(u, v, w)$ with respect to the origin of the fixed coordinate can be calculated as

$$\mathbf{e} = d_w \mathbf{w}, \tag{4}$$

where d_w is the distance between the origins of coordinate systems $E(u, v, w)$ and $P(x, y, z)$.

Inversely, if the location of $E(u, v, w)$ is known, the three angular geometric parameters can be found as

$${}^{w}\theta_{yz} = \operatorname{atan2}(w_y, w_z), \tag{5}$$

$${}^{w}\theta_{xz} = \operatorname{atan2}(w_x, w_z), \tag{6}$$

$${}^{x}\theta_{uv} = \cos^{-1}\left(\frac{\mathbf{u}\cdot\mathbf{a}'}{|\mathbf{u}||\mathbf{a}'|}\right). \tag{7}$$

Note that 'atan2' denotes the two-argument arctangent function.

Pivoting Motion
It has been shown that the surgical instrument held by an MIS robot should be manipulated with a 4-DOF pivoting motion including three rotational DOFs and one translational DOF. According to this motion constraint, three design requirements (DR) for MIS robots can be concluded as:

DR1. The end-effector should have four DOFs of motion including three rotational DOF and one translational DOF.

DR2. The axes of the three rotational DOF should intersect at some point (trocar point) which should locate some distance away from the manipulator.

DR3. The translational DOF should always point at the direction along which the surgical instrument is being inserted or retracted. In another word, the translational DOF must move along a fixed line with respect to the end-effector.

Decoupled motion
In the design goals for surgical safety, it was pointed out that a decoupled motion for the surgical instrument could suggest more confidence in safety. In response to this concern, the following design preference (DP) for MIS robotic manipulators can be written:

DP1. A decoupled motion of the end-effector of the robot is preferred.

Furthermore, referring to Figure 2, another design preference for decoupled motion is suggested as follows:

DP2. A better decoupled design is that part or all of (1) the two orientation angles ${}^{P}\theta_x$ and ${}^{P}\theta_y$, (2) the spin rotation angle ${}^{E}\theta_w$, and (3) the axial translation ${}^{E}d_w$ are uncoupled with the others.

Considering both design preferences DP1 and DP2, the best decoupled MIS robot will have every manipulated DOF of ${}^{P}\theta_x$, ${}^{P}\theta_y$, ${}^{E}\theta_w$, and ${}^{E}d_w$ uncoupled from each other. Otherwise, the next best choice is that some of the four displacement variables can be independently controlled.

Workspace
Workspace determination is a critical design task for surgical robots. According to the motion constraint of the surgical instrument, the design requirements and design preference in terms of the workspace generation for MIS robots can be realized as follows:

DR4. The workspace of the end-effector must be (mechanically) confined as a single point or an extremely small spatial volume at the entry point.

†In kinematics, the Rodrigues' formula is a mathematic formulation used to represent a spherical displacement of a rigid body. Given three associated parameters with the direction of rotation and one parameter with the angle of rotation, the orientation of a rigid body can be described by Rodrigues' formula.

DOI: 10.1002/rcs

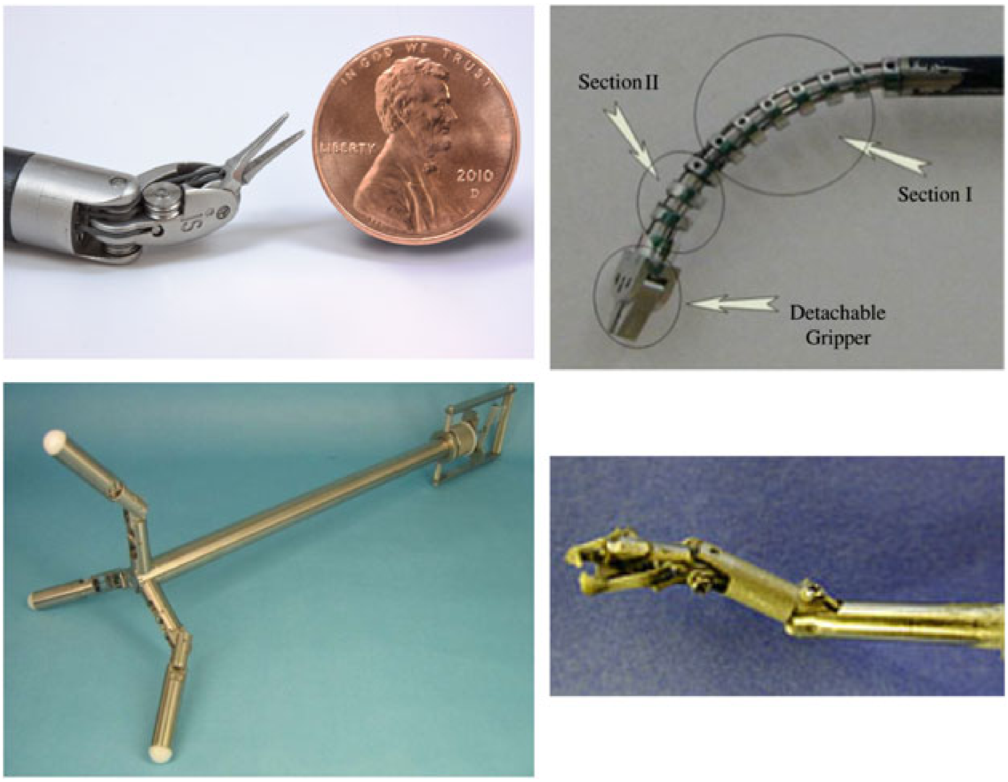

Figure 4. Tool dexterity enhancements inside the body: (a) *da Vinci* EndoWrist (18); (b) continuum robot (19); (c) multi-finger (20); (d) hyper-finger (21)

DR5. The robotic manipulator associated with the surgical instrument should be able to generate a sufficient reachable workspace‡ inside the patient's body.
DR6.The extracorporeal workspace of the manipulator should not collide with the patient.

and

DP3. The extracorporeal workspace of the manipulator should be as small as possible for preventing collision from the surgical staffs.

In the above, DR5 is a task-oriented requirement, i.e. the boundary of such a sufficient reachable workspace is dependent on the surgical task for which the robot is applied. Based on these motion constraints, we can realize that the reachable workspace volume generated by an MIS instrument tip is a cone with an apex located at the entry point. It is said that (16), by analyzing a database of general surgical tasks performed on an animal model *in vivo* in an MIS environment, 95% of the time the MIS surgical tool orientations encompass a 60° cone. Since all points within the workspace cone are expected to be approachable by the instrument at a range of angles, this cone-like workspace is proposed to be not only a reachable workspace but a partially dexterous workspace.§

Unfortunately, it is obvious that, under a pivoting constraint at the end-effector, it is impossible to generate an intra-cavity dexterous workspace by either a serial- or parallel-type robot. A frequently used strategy for dealing with this limitation is to enhance the dexterity at the instrument tip inside the body (17). This can be done by attaching a higher-DOF mechanism at the instrument tip, e.g. the *da Vinci*'s EndoWrist (Figure 4(a)), continuum robots (Figure 4(b)), or mini-humanoid robotic hand (Figure 4(c) and (d)).

Another way to cope with the limited dexterous workspace is to reduce the level and volume of the targeted workspace into a smaller but feasible one. Practically, if the penetration depth and swept range of the surgical instrument are the major concerns (e.g., in needle-guided intervention), the workspace determination could be simplified as the generation of reachable workspace. Conversely, if the instrument orientation is the key factor (e.g., in endoscopy), the orientation workspace** (22) is suitable to be adopted for the workspace synthesis task. For those designs in which both reachable and orientation workspace volumes are equally important (e.g., in laparoscopy), a compromise between these two workspaces can be considered. To design such a compromise system, optimization techniques have been frequently employed (16,23–25) where weight functions can be used to represent the significance and importance of the types of

‡A *reachable workspace* is the volume of space within which every point can be reached by the end-effector in at least one orientation.
§A *dexterous workspace* is the volume of space within which every point can be reached by the end-effector in all possible orientations.

**The *orientation workspace* is the set of all attainable orientations of the end-effector about a fixed point.

DOI: 10.1002/rcs

workspace concerned. Further, it has also been reported that the workspace boundary can be augmented by optimizing some other environmental factors, e.g., the position of the entry port in the patient's body (26–29) and the placement of the robotic manipulator (5,27,30).

Isotropy

Isotropy (31), sometimes referred to as the manipulability (8,32) of surgical robots, is a measure that indicates the motion and force/torque transmission abilities of a robotic manipulator in a given configuration. A robotic manipulator is said to be in an isotropic configuration when its actuation motions and forces can be best reflected onto the end-effector in this configuration. Furthermore, a manipulator is said to be *fully-isotropic* if it is isotropic throughout the entire workspace (33). Theoretically, an n-DOF robotic manipulator is fully-isotropic if the following equation holds throughout the workspace:

$$\dot{\mathbf{x}}_H = \mathbf{J}_{\mathrm{T}}\dot{\mathbf{q}}, \tag{8}$$

where $\dot{\mathbf{x}}_H = [\dot{x}_1, \dot{x}_2, \ldots, \dot{x}_n]^{\mathrm{T}}$ is an $n \times 1$ vector that expresses the velocity space of a point H on the end-effector with respect to the fixed coordinate, $\dot{\mathbf{q}} = [\dot{q}_1, \dot{q}_2, \ldots, \dot{q}_n]^{\mathrm{T}}$ is the velocity vector of the n actuated joints, and $\mathbf{J}_{\mathrm{T}}$ is the Jacobian matrix that satisfies the following conditions:

$$\dot{x}_k = f(\dot{q}_k) \quad \text{for } k = 1 \text{ to } n. \tag{9}$$

From Equations (8) and (9), we can quickly obtain one feasible solution for $\mathbf{J}_{\mathrm{T}}$. We observe that when $\mathbf{J}_{\mathrm{T}}$ is a diagonal matrix, Equations (8) and (9) can be satisfied simultaneously. Furthermore, if all the diagonal elements of $\mathbf{J}_{\mathrm{T}}$ are identical, the velocity ratios $\dot{x}_k/\dot{q}_k$ are equal for each argument k, i.e., the forces/torques transmissibility for each actuation is equal. However, we should notice that to satisfy Equations (8) and (9), $\mathbf{J}_{\mathrm{T}}$ is not necessarily a diagonal matrix. The diagonal matrix is merely a special case of $\mathbf{J}_{\mathrm{T}}$, which suggests a relatively simple Jocobian when determining the fully-isotropic configurations for the robot.

Isotropy can be used as an index to show the force/torque measurements at the tool tip of the surgical instrument. For MIS robots, isotropy implies the response of the actuation command on the surgical instrument, i.e., how well the motion and force generated by the actuations can be delivered to the instrument. Reversely, it also implies the response of the tissue-to-tool force or torque on the actuations, which will be investigated when considering the haptic design of MIS robots. Therefore, a design preference in terms of isotropy for MIS robots can be specified as follows:

DP4. A robotic manipulator having good isotropy over the entire workspace is preferred.

Notice that the isotropic conditions of Equations (8) and (9) relate the input variables to the velocity of the end-effector in the fixed coordinates. However, when the surgical tool motion is expressed in the four re-coordinated displacements as shown in Figure 2, Equation (8) is no longer suitable for indicating the practically-usable isotropic configuration of an MIS robot. To overcome this problem, a task-oriented fully-isotropic MIS robotic manipulator condition can be employed. For a non-redundant MIS robot (i.e., the number of actuated joints is equal to the mobility of the robot), the task-oriented fully-isotropic condition is formulated as:

$$\begin{bmatrix} {}^{P}\dot{\theta}_x \\ {}^{P}\dot{\theta}_y \\ {}^{E}\dot{\theta}_w \\ {}^{E}\dot{d}_w \end{bmatrix} = \mathbf{J}' \begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \\ \dot{q}_3 \\ \dot{q}_4 \end{bmatrix}, \tag{10}$$

where $\dot{q}_1$, $\dot{q}_2$, $\dot{q}_3$, and $\dot{q}_4$ are the velocities of the four actuated joints and $\mathbf{J}'$ is a task-orientated Jacobian matrix that satisfies the following conditions:

$${}^{P}\dot{\theta}_x = f(\dot{q}_1) \tag{11a}$$

$${}^{P}\dot{\theta}_y = f(\dot{q}_2) \tag{11b}$$

$${}^{E}\dot{\theta}_w = f(\dot{q}_3) \tag{11c}$$

$${}^{E}\dot{d}_w = f(\dot{q}_4) \tag{11d}$$

We should notice that, in Equation (10), the velocity space of the end-effector is expressed with respect to two different referencing coordinates such that a practically-usable isotropic condition for MIS needs can be suitably described. Accordingly, the Jacobian matrix $\mathbf{J}'$ is not the conventional Jacobian but a modified, task-oriented Jacobian. Because the units of the elements in the task-oriented Jacobian are inconsistent, one should be very careful when manipulating this modified Jacobian matrix.

Theoretically, the task-oriented fully-isotropic robot is a superior candidate to pursue not only kinematic decouplability but also force sensibility. In practical situations, however, a fully-isotropic or a task-oriented fully-isotropic MIS robot is very difficult to create. In general, an optimized design for the isotropic condition is used when designing an MIS robot. For example, some MIS robots have been proposed with optimum isotropy determined via optimization techniques (16,24,34) or by analytical selection (26,32) of the condition number from Jacobian analysis or alternative measures. Another approach shows that better isotropy for an MIS robot can be determined based on selection of the optimal RCM position (35,36).

Backdrivability

The use of backdrivable or non-backdrivable transmission in surgical robots has been an essential but somewhat controversial discussion for years. Both backdrivable and non-backdrivable transmissions have their advantages/disadvantages when different design goals are taken into account. A backdrivable transmission permits the surgical tool to be manually repositioned in the case an unexpected power failure, while a non-backdrivable

DOI: 10.1002/rcs

transmission suggests more confidence in safety since the manipulator will remain motionless following a power failure. When negotiating the trade-off between backdrivable and non-backdrivable systems, using a backdrivable transmission with a complementary static balancing mechanism may be an adequate solution to deal with the case of power loss. More discussions on the pros and cons of transmission backdrivability for surgical robots can be found elsewhere (2,5).

Redundancy

A redundant robotic manipulator is a mechanism that has redundant actuations or redundant degrees of freedom, namely actuation redundancy and kinematic redundancy. Actuation redundancy (37) occurs when the number of actuations is larger than the mobility of the mechanisms. Kinematic redundancy (38) is achieved by adding kinematic links and joints as well as actuations to the mechanism such that the mobility and number of actuations of the mechanism are increased (but are equal to each other). For example, if a planar serial robot is composed of three parallel revolute joints, its end-effector can theoretically approach any point with any orientation on a plane, i.e., a planar motion. Then, if we add one more revolute joint, which is also parallel to the three joints, into the robot, the end-effector can still have the planar motion but the numbers of links and joints of the robot are increased. In such a situation, we say that the robot is kinematically redundant.

In general robotic applications, actuation redundancy and kinematic redundancy are employed to guarantee a larger workspace, increase the dexterity, and avoid configuration singularity. For surgical robots, in particular, they can also be used to produce greater confidence in safety. Theoretically speaking, actuation redundancy furnishes more degrees of freedom for control flexibility, for which the possibility of potential hazards caused by an unwitting failure of control or by the unexpected movement of the patient body could be reduced. On the other hand, kinematic redundancy provides additional DOFs, which allow the robot to be reconfigured without changing the position/orientation of the instrument to adapt to a more flexible OR set-up (39). In most MIS robots where redundancy is introduced, actuation redundancy appears to be much more frequently used than kinematic redundancy. A major reason may be that actuation redundancy can significantly increase the safety of the robot. Another reason may be that the mechanical structure of a kinematically redundant robot will be more complex, so that the extracorporeal workspace of the robot will be unfavorably increased.

In conclusion, Table 1 summarizes the general design goals (DG), design requirements (DR) and design preferences (DP) for common MIS robots. The design goals outline the general surgical concerns in the MIS environment, the design requirements resolve the design goals into specific kinematic design tasks, and the design preferences suggest ways in which better performance in terms of those design goals can be achieved in MIS robots.

Remote center-of-motion mechanisms

We have learnt that an MIS robot has to manipulate its surgical instrument moving along the penetrating direction and rotating about a fixed point on the patient's body. Also, the extracorporeal workspace volume must ensure that the robotic manipulator does not collide with the patient during surgery. A general multi-DOF robot can, of course, achieve these goals based on a fine control strategy (40–43); however, a specially configured robot that accomplishes these required motions based on the structural constraint itself would be much better because the potential hazard for both surgeon and patient caused by any control or coordination failure can be automatically avoided.

The above motivation has encouraged researchers to develop a mechanism that can output a fixed rotational center located some distance away from the robot structure itself. Based on this, the concept of *remote center-of-motion* (RCM) was devised (6). Geometrically, an RCM is a fixed point associated with a mechanism about which some link(s) in the mechanism rotate. In addition, this point should be located outside the workspace volume generated by all the other links when the mechanism is driven over a given range of motion. Briefly, we can immediately understand that an RCM is a fixed center of rotation of a link that should locate outside the workspace of the mechanism; an RCM mechanism is a mechanism having one or more RCMs; and, an RCM robot is a robot that contains one or more RCM mechanisms for generating RCMs.

Decoupled remote center-of-motion mechanisms

To further reduce the control complexity and enhance the manipulation convenience, the decoupled remote center-of-motion mechanism has been suggested (6). The decoupled kinematics can greatly reduce the control complexity and increase the confidence in safety. Further, it admits more rapid manual positioning of the entire mechanism or of selected subsets of the degrees of freedom.

A decoupled RCM mechanism is an RCM mechanism in which the pivoting rotational DOFs and the associated translational DOF, if any, are either partially or fully decoupled. More specifically, consider a group of variables $D = (x_1, x_2, \ldots, x_i)$, $i = 1$ to n, that specifies the motion space of the output link in a mechanism. Also, assume that the n variables in D are controlled by n actuators without redundancy. We say that variable x_i is *decoupled* from D if the value of x_i can be determined by one corresponding actuator. If there are n_j variables, $n_j < n$, whose values are independent of some actuators, we say that the DOFs of this mechanism are *partially decoupled*. If the values of all the n variables in D can be one-to-one determined by the n actuators, we say that the DOFs of this mechanism are *fully decoupled*.

DOI: 10.1002/rcs

Table 1. Kinematic design table for MIS robots

		Mechanism design issues						
		Pivoting motion	*Decoupled motion*	*Workspace*	*Isotropy*	*Backdriability*	*Redundancy*	**Design Goals**
Surgical concerns	Safety	x	x	x	x	x	x	DG1, DG2, DG3
	Accuracy				x	x		DG4
	Ergonomics			x				DG5, DG6
	Dexterity				x			DG7, DG8
Design Requirements &Design Preferences		DR1 DR2 DR3	DP1 DP2	DR4 DR5 DR6 DP3	DP4			

Design Goals (DGs)
DG1. Kinematic constraint at the entry point.
DG2. Collision-free workspace between the manipulator, surgeon and patient.
DG3. Decoupled rotational and translational degrees of freedom for the surgical instrument.
DG4. Output displacement/input displacement ratio.
DG5. Inverse of hand-eye coordination.
DG6. Rotational ability of the end-effector.
DG7. Hand tremor reduction.
DG8. Surgical movement scaling.
Design Requirements (DRs)
DR1. The end-effector should have four DOFs of motion including three rotational DOF and one translational DOF.
DR2. The axes of the three rotational DOF should intersect at some point (trocar point) which should locate some distance away from the manipulator.
DR3. The translational DOF should always point in the direction along which the surgical instrument is being inserted or retracted; i.e. the translational DOF must move along a fixed line with respect to the end-effector.
DR4. The workspace of the end-effector must be (mechanically) confined as a single point or an extremely small spatial volume at the entry point.
DR5. The robotic manipulator associated with the surgical instrument should be able to generate a sufficient reachable workspace inside patient's body.
DR6. The extracorporeal workspace of the manipulator should not collide with the patient.
Design Preferences (DPs)
DP1. A decoupled motion of the end-effector of the robot is preferred.
DP2. A better decoupled design is when part or all of (1) the two orientation angles ${}^{P}\theta_x$ and ${}^{P}\theta_y$, (2) the spin rotation angle ${}^{E}\theta_w$, and (3) the axial translation ${}^{E}d_w$ are uncoupled with the others.
DP3. The extracorporeal workspace of the manipulator should be as small as possible to prevent collisions by the surgical staff.
DP4. A robotic manipulator having good isotropy over the entire workspace is preferred.

It has been shown that a preferred displacement representation for an MIS tool is to respectively express the four DOFs in two coordinate systems, i.e., ${}^{P}\theta_x$, ${}^{P}\theta_y$, ${}^{E}\theta_w$ and ${}^{E}d_w$ in Figure 2. Therefore, the task-orientated decouplability of the RCM mechanisms for MIS applications can be classified into the following five types (Table 2).

Type I. The translational DOF is decoupled but all the rotational DOFs are coupled. In this case, the insertion length ${}^{E}d_w$ can be independently controlled by one corresponding actuator.

Type II. Some rotational DOFs are decoupled and the other DOFs (including the translational one) are coupled with each other. In this case, the orientation angles ${}^{P}\theta_x$, ${}^{P}\theta_y$ and/or ${}^{E}\theta_w$ can be either collectively or independently controlled by the corresponding actuators.

Type III. Some rotational DOFs and the translational DOF are decoupled. In this case, some of the orientation angles ${}^{P}\theta_x$, ${}^{P}\theta_y$ and ${}^{E}\theta_w$ can be either collectively or independently controlled by some actuators. And, the insertion length ${}^{E}d_w$ can be independently controlled by one other actuator.

Type IV. All rotational DOFs are decoupled but the translational DOF is dependent on the rotational ones. In this case, each of the orientation angles ${}^{P}\theta_x$, ${}^{P}\theta_y$, and ${}^{E}\theta_w$ can be independently controlled by one corresponding actuator. And, the insertion length ${}^{E}d_w$ is determined by certain actuators together.

Type V. All rotational and translational DOFs are decoupled. In this case, each of the orientation angles ${}^{P}\theta_x$, ${}^{P}\theta_y$, and ${}^{E}\theta_w$ and the insertion length ${}^{E}d_w$ can be independently controlled by one corresponding actuator, respectively.

Table 2. Types of DOF decouplability in RCM mechanisms

Decoupled type		Decoupled translational DOF: Yes	No
Decoupled rotational DOFs	None	I	–
	Some	III	II
	All	V	IV

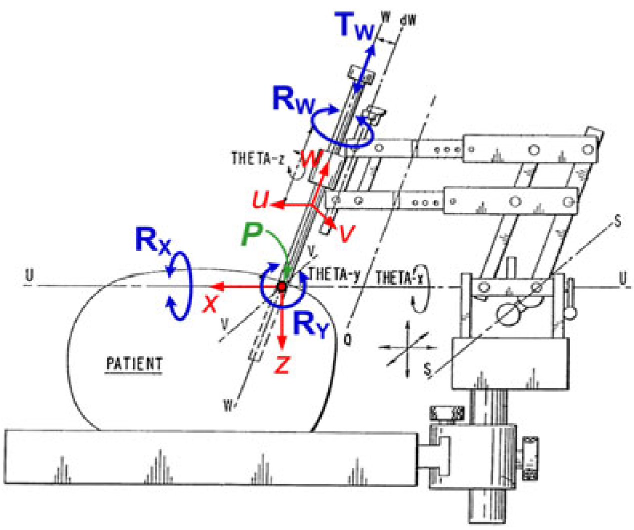

Figure 5. A partially decoupled RCM mechanism for laparoscopic surgery (6)

In existing MIS robots, Type III appears to be the most general design used in their RCM mechanisms. For example, Figure 5 shows a patented partially decoupled RCM robot used for minimally invasive laparoscopic surgery. The RCM mechanism of this robot is built based on a double parallelogram. Assume that the fixed coordinate system (*x*, *y*, *z*) is attached to the incision point *P*, and a reference coordinate system (*u*, *v*, *w*) is attached to the output link where the axial directions are defined by following Figure 2. Basically, this parallelogram-based RCM mechanism can generate two pivoting, rotational DOFs (R_X and R_Y in Figure 5) at point *P*. Two extra DOFs, i.e., one rotational DOF and one translational DOF along the axis of the rotation (R_W and T_W), are supplied by two additional actuations that are instrumented on the output link of the parallelogram. When analyzing the task-oriented decouplability, the relationship between the motion space (${}^{P}\theta_x$, ${}^{P}\theta_y$, ${}^{E}\theta_w$, ${}^{E}d_w$) of the surgical tool and the mobility space (R_X, R_Y, R_W, T_W) of the actuators can be expressed as follows:

$$ {}^{P}\theta_x = f(R_X), \tag{12a} $$

$$ {}^{P}\theta_y = f(R_X,\ R_Y), \tag{12b} $$

$$ {}^{E}\theta_w = f(R_W), \tag{12c} $$

$$ {}^{E}d_w = f(T_W). \tag{12d} $$

Equation (12a) implies that ${}^{P}\theta_x$ is a function of actuator R_X, and so do Equations (12b) to (12d). Therefore, we conclude that the task-oriented DOFs of the mechanism are partially decoupled (Type III).

It should be noted that in most MIS robots the RCM mechanism can only generate a 2-DOF orientation, i.e., ${}^{P}\theta_x$ and ${}^{P}\theta_y$. The spin rotation, ${}^{E}\theta_w$, and the translational motion, ${}^{E}d_w$, of the surgical tool are normally achieved by two additional actuations instrumented on the output link. Then, the two actuations will directly and independently drive the surgical tool to spin and to move up-and-down. Obviously, such an arrangement provides a relatively simple, direct way to complement the provision of four decoupled DOFs. However, additional payload may be induced by the auxiliary instrumentation at the end-effector and the mechanical complexity of the robot will be potentially increased.

Validation of RCMs in MIS Robots

Owing to its superior advantages in control simplicity and safety confidence, using a special-purpose MIS robot with RCM design has become the norm, rather than using a general-purpose industrial robot for MIS tasks. The RCM function may be incorporated into the robot in several ways. We can either attach an RCM mechanism module to a robotic arm (44–46), integrate some mechanical links

DOI: 10.1002/rcs

of the robotic manipulator to form an embedded RCM mechanism (47–49), or make the robotic manipulator itself an RCM mechanism (23,25). Figures 6 to 8, respectively, show examples of the three kinds of instrumentation.

Non-mechanical RCMs and passive RCMs

In RCM mechanisms, the RCM is defined and mechanically locked based on the kinematics of the mechanism. In non-mechanical RCM, however, the pivoting motion is generated by virtue of coordinated control of multiple joints in high-DOF robots. For example, Dombre *et al.* (42) reported a programmable RCM MIS robot used for endoscopy, Figure 9. The endoscopic instrument is held by the end-effector of the robot and is virtually pivoted at the trocar point by means of the computer-simulated trocar constraints. Such a task-based constraint can also be implemented by general-type industrial robots. For instance, Schneider and Troccaz (40) used a six-axis SCARA robot to perform pericardial puncture in cardiac surgery. Another similar approach is the 'virtual fixtures' concept, which can generate the absolute bound of spatial motion (as a cone for the MIS task) to constrain the robot's movement (52). The non-mechanical RCMs have a number of advantages such as changeable pivot location and increased maneuverability. For surgical applications, however, mechanical RCMs are considered safer due to their reduced DOFs, decoupled motion, controller simplicity, and locked pivot features (2).

Another special type of remote center-of-motion is the 'passive RCM' (2,53,54). In such concept, the robot uses the incision itself as a mechanical fixture to constrain tool motion but leaves some joints *passive*. For example, Figure 10 shows an active laparoscope holder that constrains laparoscope pivoting at the incision based on the concept of passive RCM. Two passive revolute joints are displaced at the distal end of the arm (Part *C* in the figure), providing the laparoscope with the ability to self-pivot at the incision point. It should be noted that the working principle of passive RCMs is different from both mechanical and non-mechanical RCMs. In passive RCM robots, the robotic arm is articulated by mechanical members; however, its RCM is achieved by non-mechanical physical constraints that are not programmable.

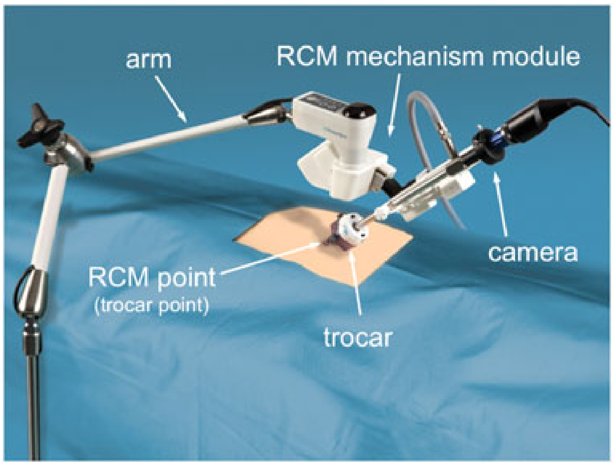

Figure 6. MIS robot with attached RCM mechanism module – *FreeHand* robot (50)

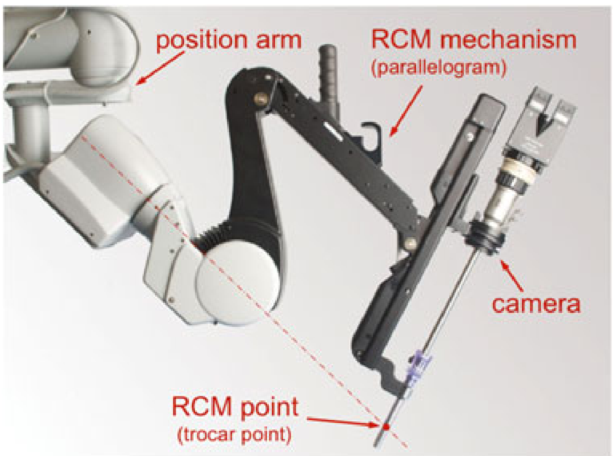

Figure 7. MIS robot with embedded RCM mechanism – *da Vinci* robotic arm (18)

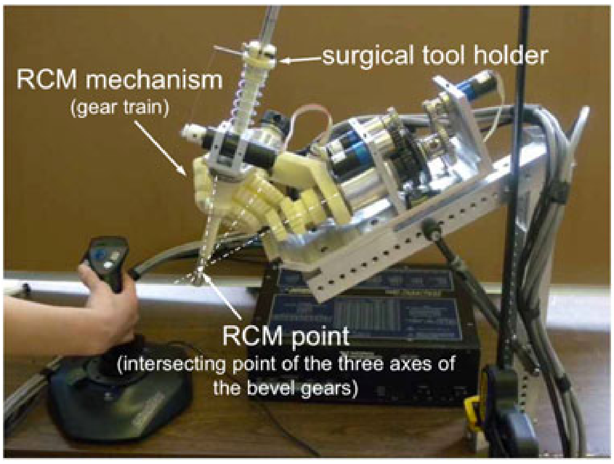

Figure 8. MIS robot foemed as a RCM mechanism – CoBRASurge robot (51)

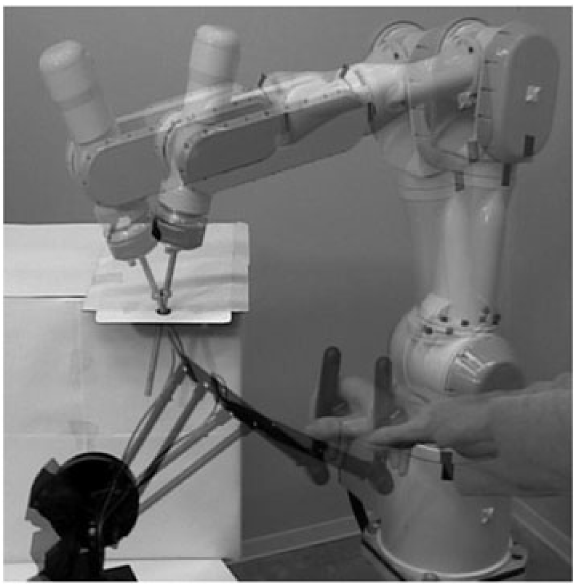

Figure 9. Non-mechanical RCM: the *MARGE* robot (42)

A classification
One way to classify the kinematic structures of MIS robots is based on the types of RCM mechanisms. Briefly, there are eight types of RCM mechanisms used in MIS robots: isocenters, circular tracking arcs, parallelograms, synchronous belt transmission, spherical linkages, gimbals, parallel wrist mechanisms, and gear trains. The conceptual schematic of each RCM mechanism type and a sample MIS robot are listed in Figure 11. In addition to the robots listed in Figure 11, some other MIS robots with RCM design are summarized in Table 3. More detailed discussion about the functions and performance of these RCM mechanisms are given elsewhere (55,56). It is noted that Table 3 summarizes only a few sample robots from many well-developed MIS robots. A more exhaustive list of surgical robots (including MIS robots) can be found in Pott *et al*. (57)

Results

Based on the kinematic design issues discussed, we compare the kinematic characteristics of the eight RCM mechanism types in Table 4. The RCM DOFs, motion decouplability, extracorporeal workspace, task-oriented isotropy, and backdrivability of the RCM mechanisms are listed in the table. The results are reached based on the authors' experience and study of the literatures and devices in both fields of kinematics and surgical robotics.

Discussion

4-DOF 3R1T RCM mechanisms

It is shown that the generation of an n-DOF nR ($n = 2$ or 3) pivoting rotation is easily achievable by most RCM mechanism types. When the translational DOF is also considered, an $(n + 1)$-DOF $nR1T$ RCM mechanism can be derived by instrumenting an auxiliary actuator onto an nR RCM mechanism. From the kinematic point of view, this integration concept is of course a feasible design for fulfilling the required surgical DOFs and for providing motion decouplability. From the static point of view, however, such additional instrumentation can increase the payload at the output link, which could bring unwelcome problems such as large inertia, increased vibration, reduced force sensibility, etc.

Without using the auxiliary actuator mounted on the end-effector, the provision of an $nR1T$ pivoting motion may be made by using an $(n + 1)$-DOF $nR1T$ serial or parallel robot with RCMs. For serial robots, such an $nR1T$ pivoting motion can be obtained by suitably configuring and articulating the kinematic joints of the robot (95). However, the problems induced by the additional payloads are still not negligible. In contrast, using parallel robots with RCMs may be a better solution for compensating the additional payload problem. There have been a number of $3R1T$ 4-DOF RCM parallel robots available for surgical applications (96,97). Nevertheless, motion decouplability and fully-isotropic configurations of the 4-DOF $3R1T$ parallel robots has not been reported.

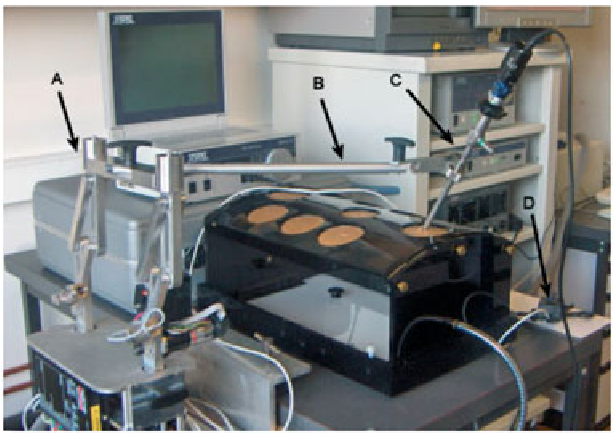

Figure 10. Passive RCM: the *EVOLAP* laparoscope holder (7)

Motion decouplability

In terms of motion decouplability, the best RCM mechanism is the one whose task-oriented DOFs are fully decoupled. In overview of the current MIS robots, however, most RCM mechanisms are only partially decoupled. As illustrated by the example in Figure 5, the two rotational DOFs expressed in the fixed coordinate are coupled with each other, while the other rotational DOF and the translational DOF expressed in the end-effector's coordinate are fully decoupled (Equation (12a) to (12d)). The outcome of the two coupled rotational DOFs is due to the fact that most RCM mechanisms are based on a serial-type structure. Under such a pattern, the location of the rotation axis of the second rotational DOF is dependent on the displacement of the first rotational DOFs. This leads to the fact that the displacement of the second rotational DOF cannot be invariant in the fixed coordinate system while the first rotational DOF is activating. An intuitive approach for solving this problem might be the use of parallel robotic manipulators in which all actuated joints can be intentionally attached to the base. However, such a fully-decoupled 4-DOF $3R1T$ in-parallel actuated mechanisms (for either of general fully-decoupled and task-oriented fully-decoupled types) has not yet been reported as far as we are aware.

Task-oriented fully-isotropic design

The task-oriented fully-isotropic RCM mechanism is extremely useful for providing more confidence in safety, simplifying the joint coordination, and sensing the reaction force and torque on the tissue for MIS needs. Unfortunately, while task-oriented fully decoupled mechanisms are still under investigation, a task-oriented fully-isotropic RCM mechanism for MIS applications has not been achieved so

DOI: 10.1002/rcs

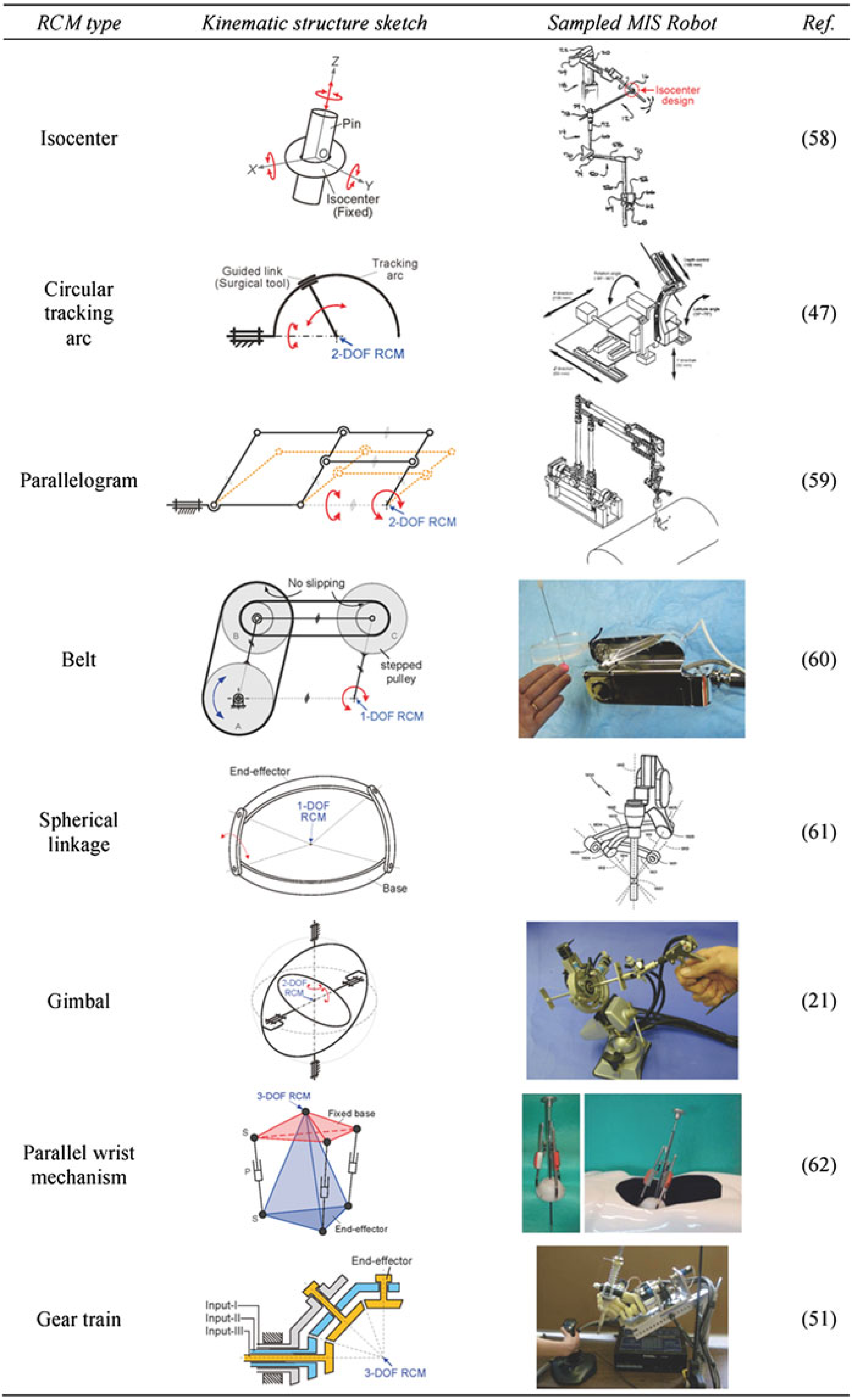

Figure 11. Eight RCM mechanism types and example of their MIS robots

DOI: 10.1002/rcs

Table 3. Sample minimally invasive surgical robots using RCMs

Robot	Institution	Country	Year	RCM DOF*	RCM Type	Ref.
AcuBot	Johns Hopkins Univ./ Georgetown Univ.	USA	2001	2R	synchronous belt	(44,63)
Active Trocar	Univ. of Tokyo	Japan	2002	2R	parallelogram	(64)
AESOP	Computer Motion	USA	1992	2R	passive RCM	(65)
ARTEMIS	Eberhard Karls Univ./ Karlsruhe Res. Center	Germany	1996	2R	parallelogram	(45,66)
Black Falcon	Massachusetts Institute of Technology	USA	1998	2R	parallelogram	(49)
BlueDRAGON	Univ. of Washington	USA	2002	2R	parallelogram	(59)
CoBRASurge	Univ. of Nebraska-Lincoln	USA	2008	3R	gear train	(23,51)
CLEM	Institut Albert Bonniot	France	2002	3R1T	isocenter (flexible straps)	(67)
da Vinci	Intuitive Surgical	USA	1999	2R	parallelogram	(48,68)
EndoBot	Rensselaer Polytechnic Institute	USA	2001	2R	circular tracking arc	(69)
EVOLAP	UcLouvain/LIRMM	Belgium	2009	2R	parallelogram with passive RCM	(7)
FIPS Endoarm	Eberhard Karls Univ./ Karlsruhe Res. Center	Germany	1999	2R	circular tracking arc	(70)
KineMedic	German Aerospace Center (DLR)	Germany	2006	-	non-mechanical	(24,71)
LARS	IBM	USA	1995	2R	parallelogram	(72,73)
MARGE	French National Research Center	France	2001	-	non-mechanical	(42,74)
MARS	Technion—Israel Institute of Technology	Israel	2003	-	non-mechanical	(75)
MC^2E	Univ. of Paris	France	2004	2R	spherical linkage	(76,77)
MHU	Miguel Hernandez Univ. *et al*.	Spain	2010	3R	parallel wrist manipulator	(62)
MicroHand	Tianjin University	China	2005	2R	crcular tracking arc	(32,78)
MicroHand A	Tianjin University	China	2010	2R	synchronous belt	(79)
Naviot	Hitachi	Japan	2003	2R	isocenter	(80)
Neurobot	Imperial College London	UK	2000	2R	parallelogram	(81)
PADyC	Universite' Joseph Fourier	France	2001	-	non-mechanical	(40)
PAKY-RCM	Johns Hopkins Univ.	USA	1998	2R	synchronous belt	(60)
PantoScope	Swiss Federal Institute of Technology	Switzer- land	1997	2R	parallelogram	(82)
Probot	Imperial College London	UK	1991	2R	circular tracking arc	(83)
RAVEN	Univ. of Washington	USA	2006	2R	spherical linkage	(34)
Siemens CT	Siemens AG	Germany	2000	2R	parallelogram	(84)
SpineNav	Nankai Univ./Dalian Neusoft Institute of Information	China	2008	-	non-mechanical	(85)
Steady-Hand	Johns Hopkins Univ.	USA	1999	2R	synchronous belt	(86)
UBC-US	Univ. of British Columbia	Canada	1999	2R	parallelogram	(87)
UCB/UCSF	UC Berkeley/UC San Fran.	USA	1999	-	non-mechanical	(43)
UMI	Univ. of Tokyo	Japan	2002	1R	circular tracking arc	(88)
UT-LAP	Univ. of Tokyo	Japan	1999	2R	isocenter	(89)
UT-MRI	Univ. of Tokyo	Japan	2002	1R	non-mechanical	(90)
UT-NEU	Univ. of Tokyo	Japan	1998	2R	circular tracking arc	(47)
VESALIUS	K.U.Leuven	Belgium	2003	2R	parallelogram	(91)
ViKY	EndoControl	France	2003	2R	circular tracking arc	(46,92,93)
Zeus	Computer Motion	USA	1998	3R	passive RCM	(58,94)

*The DOFs provided by the auxiliary instrumentation on the RCM mechanism are not includedd.

Table 4. Comparison of the MIS robots based on RCM mechanism type

"Mechanism design issues" vs. "RCM mechanism types"			RCM mechanism type: *Isocenter*	*Circular tracking arc*	*Parallelogram*	*Synchronous belt*	*Spherical linkage (open chain)*	*Spherical linkage (closed chain)*	*Gimbal*	*Parallel wrist mechanism*	*Gear train*
Mechanism design issues	RCM DOFs	2-DOF rotation (2*R*)	A	A	A	A	A	A	A	A	A
		3-DOF rotation (3*R*)	A	A	B	B	A	A	A	A	A
		2-DOF rot. + 1-DOF trans (2*R*1*T*)	A	B	B	B	B	B	B	B	B
		3-DOF rot. + 1-DOF trans (3*R*1*T*)	A	B	B	B	B	B	B	B	B
	Task-oriented 4-DOF decouplability	Type-I (*T* decoupled)	-	B	B	B	B	B	B	B	B
		Type-II (Some *R*'s decoupled)	-	A	A	A	A	-	A	A	A
		Type-III (Some *R*'s & *T* decoupled)	-	B	B	B	B	-	B	B	B
		Type-IV (All *R*'s decoupled)	-	-	-	-	-	-	-	A	-
		Type-V (All *R*'s & *T* decoupled)	-	-	-	-	-	-	-	B	-
Extracorporeal workspace			-	A	A	A	A	A	-	A	A
Task-oriented fully-isotropic 3*R*1*T*			-	-	-	-	-	-	-	B	-
Backdriability			-	A	A	A	A	A	A	A	A

[A]Achievable/available.
[B]Achievable/available but auxiliary instrumentation required.
[-]Not achievable/applicable.

far. Therefore, this is still an interesting and open problem for kinematicans.

Conclusions

The kinematic design considerations and mechanism development of the robotic manipulators used for minimally invasive surgery have been discussed. The motion constraints of the surgical instrument maneuvered by MIS robots were analyzed. A set of design goals, design requirements, and design preferences formed in response to the surgical requirements for MIS robots was proposed. In particular, the remote center-of-motion mechanism was reviewed, and its kinematic decouplability was comprehensively studied. Eight RCM mechanism types were classified and compared. Finally, the current limitations and ongoing challenges in terms of kinematics for MIS robots were discussed. It is anticipated that the work done here can lead to more inspirational outcomes that could improve or solve the existing kinematic limitations in minimally invasive surgical robots.

Acknowledgements

The first author acknowledges the financial support from the National Science Council, Taiwan, ROC (Grant No. NSC-095-SAF-I-564-017-TMS) and the King's College London Graduate School Scholarship and Overseas Research Studentship (ORS) Award of United Kingdom.

References

1. Kwoh YS, Hou J, Jonckheere EA, Hayati S. A robot with improved absolute positioning accuracy for CT guided stereotactic brain surgery. *IEEE Trans Biomed Eng* 1988; **35**(2): 153–160.
2. Taylor RH, Stoianovici D. Medical robotics in computer-integrated surgery. *IEEE Trans Robotics Automat* 2003; **19**(5): 765–781.
3. Davies BL. A discussion of safety issues for medical robots. In *Computer-Integrated Surgery: Technology and Clinical Applications*, Taylor RH, Lavallée S, Burdea GC, Mösges R (eds). MIT Press: Cambridge, MA, 1996; 287–296.
4. Fei B, Ng WS, Chauhan S, Kwoh CK. The safety issues of medical robotics. *Reliab Eng Syst Saf* 2001; **73**(2): 183–192.
5. Funda J, Eldridge BN, Gruben K, *et al*. Comparison of two manipulator designs for laparoscopic surgery. In *Proceedings of SPIE - The International Society for Optical Engineering*, 1995; 172–183.
6. Taylor RH, Funda J, Grossman DD, *et al*. Improved remote center-of-motion robot for surgery. European Patent No. EP0595291, 1994.
7. Herman B, Dehez B, Duy KT, *et al*. Design and preliminary in vivo validation of a robotic laparoscope holder for minimally invasive surgery. *Int J Med Robotics Comput Assist Surg* 2009; **5**(3): 319–326.
8. Konietschke R, Ortmaier T, Weiss H, *et al*. Manipulability and accuracy measures for a medical robot in minimally invasive surgery. In *On Advances in Robot Kinematics*, Lenarčič J, Galletti C (eds). Kluwer Academic: Dordrecht, Netherlands, 2004; 191–198.
9. Berguer R. Surgery and ergonomics. *Arch Surg* 1999; **134**(9): 1011–1016.
10. Kaya OI, Moran M, Ozkardes AB, *et al*. Ergonomic problems encountered by the surgical team during video endoscopic surgery. *Surg Laparosc Endosc Percut Tech* 2008; **18**(1): 40–44.
11. Dai JS, Holland N, Kerr DR. Finite twist mapping and its application to planar serial manipulators with revolute joints. *Proc IME, Part C: J Mech Eng Sci* 1995; **209**(43): 263–271.
12. Cui L, Dai JS. Posture, workspace and manipulability of the metamorphic multifingered hand with an articulated palm. *ASME Trans, J Mechanisms Robotics* 2011; **3**(2): 021001(1–7).
13. Stylopoulos N, Rattner D. Robotics and ergonomics. *Surg Clinics N Am* 2003; **83**(6): 1321–1337.
14. Tsai L-W. *Robot Analysis: The Mechanics of Serial and Parallel Manipulators*. John Wiley & Sons: New York, 1999.
15. Dai JS. An historical review of the theoretical development of rigid body displacements from rodrigues parameters to the finite twist. *Mech Mach Theory* 2006; **41**(1): 41–52.
16. Lum MJH, Rosen J, Sinanan MN, *et al*. Kinematic optimization of a spherical mechanism for a minimally invasive surgical robot. In Proceedings of IEEE International Conference on Robotics and Automation; 26 April-1 May 2004, New Orleans, LA, USA; 829–834.
17. Taylor RH. A perspective on medical robotics. *Proc IEEE* 2006; **94**(9): 1652–1664.
18. Intuitive Surgical, Inc., http://www.intuitivesurgical.com/
19. Simaan N, Taylor R, Flint P. A dexterous system for laryngeal surgery: multi-backbone bending snake-like slaves for teleoperated dexterous surgical tool manipulation. In Proceedings of IEEE International Conference on Robotics and Automation; 26 April-1 May 2004, New Orleans, LA, USA; 351–357.
20. Takayama T, Omata T, Futami T, Akamatsu H, Ohya T, Kojima K, Takase K, Tanaka N. Detachable-fingered hands for manipulation of large internal organs in laparoscopic surgery. In Proceedings of IEEE International Conference on Robotics and Automation; 10–14 April 2007, Roma, Italy; 244–249.
21. Ikuta K, Sasaki K, Yamamoto K, Shimada T. Remote microsurgery system for deep and narrow space - development of new surgical procedure. In *Proceedings of Medical Image Computing and Computer-Assisted Intervention - MICCAI 2002*. : Tokyo, Japan, 25–28 September, 2002; 163–172.
22. Bonev IA, Ryu J. A new approach to orientation workspace analysis of 6-DOF parallel manipulators. *Mech Mach Theory* 2001; **36**(1): 15–28.
23. Zhang X, Nelson CA. Kinematic analysis and optimization of a novel robot for surgical tool manipulation. *ASME Trans, J Med Devices* 2008; **2**(2): 021003.
24. Konietschke R, Ortmaier T, Hagn U, *et al*. Kinematic design optimization of an actuated carrier for the DLR multi-arm surgical system. In Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems; 9–15 October 2006, Beijing, China; 4381–4387.
25. Li T, Payandeh S. Design of spherical parallel mechanisms for application to laparoscopic surgery. *Robotica* 2000; **20**(2): 133–138.
26. Çavuşoğlu MC, Villanueva I, Tendick F Workspace analysis of robotic manipulators for a teleoperated suturing task. In Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems; 29 October-3 November 2001, Maui, Hawaii, USA.
27. Adhami L, Coste-Manière È. Optimal planning for minimally invasive surgical robots. *IEEE Trans Robotics Automat* 2003; **19**(5): 854–863.
28. Pan B, Fu Y, Wang S. Position planning for laparoscopic robot in minimally invasive surgery. In Proceedings of IEEE International Conference on Mechatronics and Automation; 5–8 August 2007, Harbin, China; 1056–1061.
29. Austad A, Elle OJ, Røtnes JS. Computer-aided planning of trocar placement and robot settings in robot-assisted surgery. In CARS 2001 - Computer Assisted Radiology and Surgery: Proceedings of the 15th International Congress and Exhibition; 27–30 June 2001, Berlin, Germany; 1020–1026.
30. Abdel-Malek K, Yu W, Yang J. Placement of robot manipulators to maximize dexterity. *Int J Robotics Automat* 2004; **19**(1): 6–14.
31. Salisbury JK, Craig JJ. Articulated hands: force control and kinematic issues. *Int J Robotics Res* 1982; **1**(1): 4–17.
32. Wang S, Li Q, Ding J, Zhang Z. Kinematic design for robot-assisted laryngeal surgery systems. In Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems; 9–15 October 2006, Beijing, China; 2864–2869.
33. Carricato M, Parenti-Castelli V. Singularity-free fully-isotropic translational parallel mechanisms. *Int J Robotics Res* 2002; **21**(2): 161–174.

34. Lum MJH, Rosen J, Sinanan MN, Hannaford B. Optimization of a spherical mechanism for a minimally invasive surgical robot: theoretical and experimental approaches. *IEEE Trans Biomed Eng* 2006; **53**(7): 1440–1445.
35. Locke RCO, Patel RV. Optimal remote center-of-motion location for robotics-assisted minimally-invasive surgery. In Proceedings of IEEE International Conference on Robotics and Automation; 10–14 April 2007, Roma, Italy; 1900–1905.
36. Trejos AL, Patel RV, Ross I, Kiaii B. Optimizing port placement for robot-assisted minimally invasive cardiac surgery. *Int J Med Robotics Comput Assist Surg* 2007; **3**(4): 355–364.
37. Dasgupta B, Mruthyunjaya TS. Force redundancy in parallel manipulators: theoretical and practical issues. *Mech Mach Theory* 1998; **33**(6): 727–742.
38. Wang J, Gosselin CM. Kinematic analysis and design of kinematically redundant parallel mechanisms. *ASME Trans, J Mech Design* 2004; **126**(1): 109–118.
39. Ortmaier T, Weiss H, Falk V. Design requirements for a new robot for minimally invasive surgery. *Ind Robot* 2004; **31**(6): 493–498.
40. Schneider O, Troccaz J. A six-degree-of-freedom passive arm with dynamic constraints (PADyC) for cardiac surgery application: preliminary experiments. *Comput Aided Surg* 2001; **6**(6): 340–351.
41. Ghafoor A, Dai JS, Duffy J. Fine motion control based on constraint criteria under pre-loading configurations. *J Robotic Syst* 2000; **17**(4): 171–185.
42. Dombre E, Michelin M, Pierrot F, *et al*. MARGE Project: design, modeling and control of assistive devices for minimally invasive surgery. In *Proceedings of Medical Image Computing and Computer-Assisted Intervention - MICCAI 2004*. : Saint-Malo, France, 26–29 September, 2004; 1–8.
43. Çavuşoğlu MC, Tendick F, Cohn M, Sastry SS. A laparoscopic telesurgical workstation. *IEEE Trans Robotics Automat* 1999; **15**(4): 728–739.
44. Stoianovici D, Cleary K, Patriciu A, *et al*. AcuBot: a robot for radiological interventions. *IEEE Trans Robotics Automat* 2003; **19**(5): 927–930.
45. Schurr MO, Arezzo A, Neisius B, *et al*. Trocar and instrument positioning system TISKA: an assist device for endoscopic solo surgery. *Surg Endosc* 1999; **13**(5): 528–531.
46. Gumbs AA, Crovari F, Vidal C, *et al*. Modified robotic lightweight endoscope (ViKY) validation in vivo in a porcine model. *Surg Innov* 2007; **14**(4): 261–264.
47. Hata N, Masamune K, Kobayashi E, *et al*. Needle insertion manipulator for CT- and MR-guided stereotactic neurosurgery. In *Interventional MR: Techniques and Clinical Experience*, Jolesz FA, Young IR (eds). Martin Dunitz: London, 1998; 99–106.
48. Morley TA, Wallace DT. Roll-Pitch-Roll Surgical Tool. US Patent No. 2005204851. 2005.
49. Madhani AJ, Niemeyer G, Salisbury JK, Jr. The Black Falcon: a teleoperated surgical instrument for minimally invasive surgery. In Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems; 13–17 October 1998, Victoria, BC, Canada; 936–944.
50. Prosurgics, Inc., http://www.freehandsurgeon.com/
51. Lehman AC, Tiwari MM, Shah BC, *et al*. Recent advances in the CoBRASurge robotic manipulator and dexterous miniature in vivo robotics for minimally invasive surgery. *Proc IME, Part C: J Mech Eng Sci* 2010; **224**(7): 1487–1494.
52. Li M, Kapoor A, Taylor RH. Telerobotic control by virtual fixtures for surgical applications. In *Springer Tracts in Advanced Robotics*, Vol. **31**. Springer: Berlin Heidelberg, Germany, 2007; 381–401.
53. Begin E, Gagner M, Hurteau R, de Santis S, Pomp A. A robotic camera for laparoscopic surgery: conception and experimental results. *Surg Laparosc Endosc* 1995; **5**(1): 6–11.
54. Armstrong Healthcare, Inc., http://www.armstrong-healthcare.com/
55. Kuo C-H. Synthesis and applications of decoupled parallel manipulators using motion constraint generator for minimally invasive surgery. PhD thesis, Department of Mechanical Engineering, King's College London, London, UK. 2011.
56. Kuo C-H, Dai JS. Robotics for minimally invasive surgery: a historical review from the perspective of kinematics. In *International Symposium on History of Machines and Mechanisms - Proceedings of HMM 2008*, Yan H-S, Ceccarelli M (eds). Springer: Tainan, Taiwan, 10–14 November, 2008; 337–354.
57. Pott PP, Scharf H-P, Schwarz MLR. Today's state of the art in surgical robotics. *Comput Aided Surg* 2005; **10**(2): 101–132.
58. Sanchez D, Black M, Hammond S. A pivot point arm for a robotic system used to perform a surgical procedure. European Patent No. 1254642. 2002.
59. Rosen J, Brown JD, Chang L, *et al*. The BlueDRAGON - a system for measuring the kinematics and the dynamics of minimally invasive surgical tools in-vivo. In Proceedings of IEEE International Conference on Robotics and Automation; 11–15 May 2002, Washington, DC, USA; 1876–1881.
60. Stoianovici D, Whitcomb LL, Anderson JH, *et al*. A modular surgical robotic system for image guided percutaneous procedures. In *Proceedings of Medical Image Computing and Computer-Assisted Intervention - MICCAI '98*. : Cambridge, MA, USA, 11–13 October, 1998; 404–410.
61. Schena B. Center robotic arm with five-bar spherical linkage for endoscopic camera. International Patent No. WO2007114975. 2007.
62. Navarro JS, Garcia N, Perez C, *et al*. Kinematics of a robotic 3UPS1S spherical wrist designed for laparoscopic applications. *Int J Med Robotics Comput Assist Surg* 2010; **6**(3): 291–300.
63. Cleary K, Stoianovici D, Patriciu A, Mazilu D, Lindisch D, Watson V. Robotically assisted nerve and facet blocks: a cadaveric study. *Academic Radiol* 2002; **9**(7): 821–825.
64. Kobayashi Y, Chiyoda S, Watabe K, *et al*. Small occupancy robotic mechanisms for endoscopic surgery. In *Proceedings of Medical Image Computing and Computer-Assisted Intervention - MICCAI 2002*. : Tokyo, Japan, 25–28 September, 2002; 75–82.
65. Sackier JM, Wang Y. Robotically assisted laparoscopic surgery: from concept to development. In *Computer-Integrated Surgery: Technology and Clinical Applications*, Taylor RH, Lavallée S, Burdea GC, Mösges R (eds). MIT Press: Cambridge, MA, 1996; 577–580.
66. Schurr MO, Buess G, Neisius B, Voges U. Robotics and telemanipulation technologies for endoscopic surgery: a review of the ARTEMIS Project. *Surg Endosc* 2000; **14**(4): 375–381.
67. Berkelman P, Cinquin P, Troccaz J, *et al*. A compact, compliant laparoscopic endoscope manipulator. In Proceedings of IEEE International Conference on Robotics and Automation; 11–15 May 2002, Washington, DC, USA; 1870–1875.
68. Guthart GS, Salisbury JK, Jr. The Intuitive™ Telesurgery System: overview and application. In Proceedings of IEEE International Conference on Robotics and Automation; 24–28 April 2000, San Francisco, CA, USA; 618–621.
69. Kang H, Wen JT. Robotic assistants aid surgeons during minimally invasive procedures. *IEEE Eng Med Biol Mag* 2001; **20**(1): 94–104.
70. Buess GF, Arezzo A, Schurr MO, Ulmer F, Fisher H, Gumb L, Testa T, Nobman C. A new remote-controlled endoscope positioning system for endoscopic solo surgery. *Surg Endosc* 2000; **14**(4): 395–399.
71. Seibold U, Kübler B, Hirzinger G. Prototype of instrument for minimally invasive surgery with 6-axis force sensing capability. In Proceedings of IEEE International Conference on Robotics and Automation; 18–22 April 2005, Barcelona, Spain; 496–501.
72. Taylor RH, Funda J, Eldridge B, *et al*. A telerobotic assistant for laparoscopic surgery. *IEEE Eng Med Biol Mag* 1995; **14**(3): 279–288.
73. Eldridge B, Gruben K, LaRose D, *et al*. A remote center of motion robotic arm for computer assisted surgery. *Robotica* 1996; **14**(1): 103–109.
74. Michelin M, Dombre E, Poignet P, *et al*. Path planning under a penetration point constraint for minimally invasive surgery. In Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems; 30 September-5 October 2002, Lausanne, Switzerland; 1475–1480.
75. Shoham M, Burman M, Zehavi E, *et al*. Bone-mounted miniature robot for surgical procedures: concept and clinical applications. *IEEE Trans Robotics Automat* 2003; **19**(5): 893–901.
76. Zemiti N, Morel G, Ortmaier T, Bonnet N. Mechatronic design of a new robot for force control in minimally invasive surgery. *IEEE/ASME Trans Mechatron* 2007; **12**(2): 143–153.
77. Zemiti N, Ortmaier T, Morel G. A new robot for force control in minimally invasive surgery. In Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems; 28 September-2 October 2004, Sendai, Japan; 3643–3648.
78. Wang S, Ding J, Yun J, *et al*. A robotic system with force feedback for micro-surgery. In Proceedings of IEEE International Conference on Robotics and Automation; 18–22 April 2005, Barcelona, Spain; 199–204.

79. Li J, Wang S, Wang X, He C. Optimization of a novel mechanism for a minimally invasive surgery robot. *Int J Med Robotics Comput Assist Surg* 2010; **6**(1): 83–90.
80. Yasunaga T, Hashizume M, Kobayashi E, *et al*. Remote-controlled laparoscope manipulator system, Naviot™, for endoscopic surgery. In *CARS 2003 - Computer Assisted Radiology and Surgery: Proceedings of the 17th International Congress and Exhibition*, Lemke HU, Inamura K, Vannier MW, *et al*. (eds). Elsevier: London, UK, 25–28 June, 2003; 678–683.
81. Davies B, Starkie S, Harris SJ, *et al*. Neurobot: a special-purpose robot for neurosurgery. In Proceedings of IEEE International Conference on Robotics and Automation; 24–28 April 2000, San Francisco, CA, USA; 4103–4108.
82. Baumann R, Maeder W, Glauser D, Clavel R. The PantoScope: a spherical remote-center-of-motion parallel manipulator for force reflection. In Proceedings of IEEE International Conference on Robotics and Automation; 20–25 April 1997, Albuquerque, NM, USA; 718–723.
83. Davies BL, Hibberd RD, Timoney AG, Wickham JEA. A clinically applied robot for prostatectomies. In *Computer-Integrated Surgery: Technology and Clinical Applications*, Taylor RH, Lavallée S, Burdea GC, Mösges R (eds). MIT Press: Cambridge, MA, 1996; 593–601.
84. Loser MH, Navab N. A new robotic system for visually controlled percutaneous interventions under CT fluoroscopy. In *Proceedings of Medical Image Computing and Computer-Assisted Intervention - MICCAI 2000*, Delp SL, DiGoia AM, Jaramaz B (eds). Springer: Pittsburgh, Pennsylvania, USA, 11–14 October, 2000; 887–896.
85. Song Y, An G, Zhang J, Chen Y. Medical robotic system for minimally invasive spine surgery. In Proceedings of the 2nd International Conference on Bioinformatics and Biomedical Engineering (iCBBE 2008); 16–18 May 2008, Shanghai, China; 1703–1706.
86. Taylor R, Jensen P, Whitcomb L, *et al*. A steady-hand robotic system for microsurgical augmentation. *Int J Robotics Res* 1999; **18**(12): 1201–1210.
87. Salcudean SE, Zhu WH, Abolmaesumi P, *et al*. A robot system for medical ultrasound. In The 9th International Symposium of Robotics Research (ISRR '99); 9–12 October 1999, Snowbird, Utah, USA; 195–202.
88. Hong J, Dohi T, Hashizume M, *et al*. An ultrasound-driven needle-insertion robot for percutaneous cholecystostomy. *Phys Med Biol* 2004; **49**(3): 441–455.
89. Kobayashi E, Masamune K, Sakuma I, *et al*. A new safe laparoscopic manipulator system with a five-bar linkage mechanism and an optical zoom. *Comput Aided Surg* 1999; **4** (4): 182–192.
90. Kim D, Kobayashi E, Dohi T, Sakuma I. A new, compact MR-compatible surgical manipulator for minimally invasive liver surgery. In *Proceedings of Medical Image Computing and Computer-Assisted Intervention - MICCAI 2002*. : Tokyo, Japan, 25–28 September, 2002; 99–106.
91. Tang H-W, Van Brussel H, Reynaerts D, *et al*. A laparoscopic robot with intuitive interface for gynecological laser laparoscopy. In Proceedings of IEEE International Conference on Robotics and Automation; 14–19 September 2003, Taipei, Taiwan; 2646–2650.
92. Berkelman P, Boidard E, Cinquin P, Troccaz J. LER: the light endoscope robot. In Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems; 27–31 October 2003, Las Vegas, NV, USA; 2835–2840.
93. Berkelman P, Ma J. A compact modular teleoperated robotic system for laparoscopic surgery. *Int J Robotics Res* 2009; **28**(9): 1198–1215.
94. Ghodoussi M, Butner SE, Wang Y. Robotic surgery – the transatlantic case. In Proceedings of IEEE International Conference on Robotics and Automation; 11–15 May 2002, Washington, DC, USA; 1882–1888.
95. Kuo C-H, Dai JS. Structural synthesis of serial robotic manipulators subject to specific motion constraints. In Proceedings of ASME International Design Engineering Technical Conferences & Computers and Information in Engineering Conference; 15–18 August 2010, Montreal, Quebec, Canada.
96. Chung J, Cha H-J, Yi B-J, Kim WK. Implementation of a 4-DOF parallel mechanism as a needle insertion device. In Proceedings of IEEE International Conference on Robotics and Automation; 3–7 May 2010, Anchorage, Alaska, USA; 662–668.
97. Zoppi M, Zlatanov D, Gosselin CM. Analytical kinematics models and special geometries of a class of 4-DOF parallel mechanisms. *IEEE Trans Robotics* 2005; **21**(6): 1046–1055.