MR SAM: Magnetic Resonance Compatible Surgical Manipulator

Joshua Petitt and Karol Miller
Intelligent Systems for Medicine Laboratory
School of Mechanical Engineering
The University of Western Australia
Crawley/Perth 6009 WA
kmiller@mech.uwa.edu.au
http://www.mech.uwa.edu.au/ISML

Abstract

This paper discusses the optimal design of MR SAM - a robot for tool placement during magnetic resonance image-guided surgery. The robot is required to operate in a magnetic environment, therefore a unique set of constraints was placed on the design. The prime constraint was that the final design must be MR safe. This requires the actuators to be placed away from the centre of the imaging area, which led to the decision to investigate a parallel robot architecture. A work cell model was developed along with requirements for the tool motion. For detailed analysis we chose a PSUx6 kinematic structure. The robot uses parallel linear actuators to generate the motion of the tool. Investigations into the effect of geometric parameters on manipulability were performed. It was found that manipulability is maximised when the travelling plate radius is maximised and leg length is minimised. It was also found that if the actuators are arranged in a semi-circular fashion, a vertical shift in the workspace occurred, which is beneficial for the application. It was shown that the optimal base geometry uses three pairs of actuators at 120° intervals around the base and that short (< 60 cm) legs were needed to prevent interference between the scanner and the robot. The length and resolution requirements for the actuators were also found. The robot is predicted to have a spatial resolution of **<0.8 mm** and an angular resolution of <**0.5°**. The maximal workspace volume was calculated to be **0.13 m^3**. The actuators should be >**50 cm** in length and have a sensing resolution of <**3.0 x 10^{-3} mm**. This information is currently used for the detailed design and construction of a prototype.

1 Introduction

The advantages of surgical robots and manipulators are well recognized in the clinical and technical community. Precision, accuracy, and the potential for telesurgery are the prime motivations in applying advanced robot technology in surgery [Villotte et al., 1992; Taylor et al, 1995; Sackier and Wang, 1995; Schenker et al., 1995].

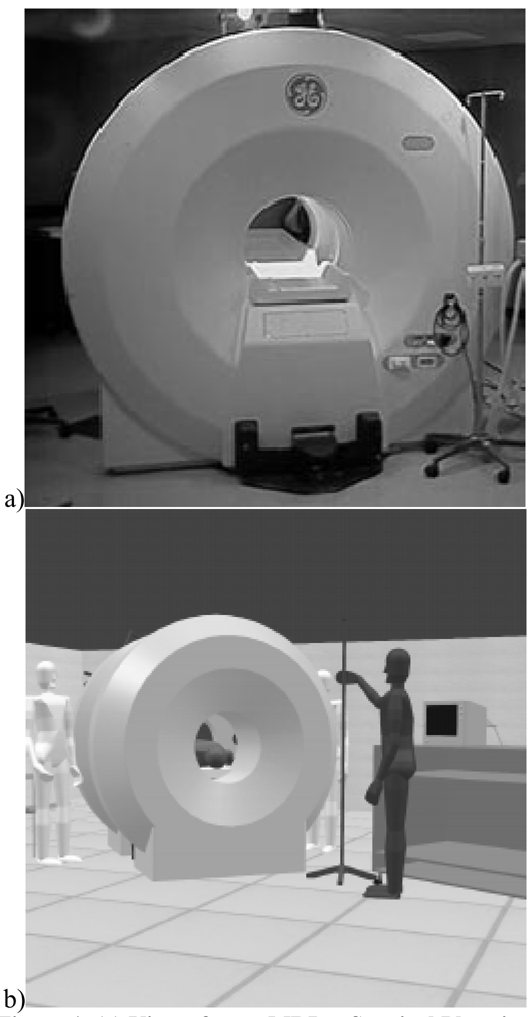
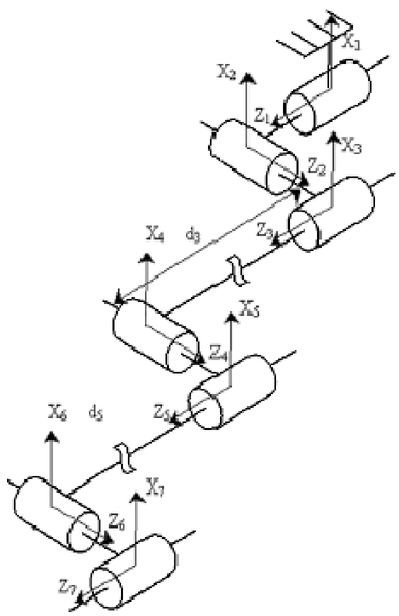

a)
b)

Figure 1. (a) View of open MRI at Surgical Planning Laboratory, Brigham and Women's Hospital (Boston, MA); (b) view of virtual operating room

Surgical robots require trajectory planning, which in practice relies upon preoperative images. If the target organ is deformable the trajectory needs to be updated according to the magnitude of the deformation. Here,



a)

Joint values

Left arm			
d	θ	a	α
0	10	0	90
0	40	0	-90
32.364	20	0	90
0	-80	0	-90
25.404	-90	0	90
0	90	0	-90
0	0	10	0

Head	
angle	value
z	0
y	0
x	0

right arm			
d	θ	a	α
0	-20	0	90
0	20	0	-90
32.364	-20	0	90
0	-60	0	-90
25.404	90	0	90
0	90	0	-90
0	0	0	0

Left leg			
d	θ	a	α
0	0	0	90
0	60	0	-90
42.63	0	0	90
0	10	0	-90
42.804	0	0	90
0	90	0	-90
0	0	0	90

Hip	
angle	value
z	0
y	10
x	0

right leg			
d	θ	a	α
0	0	0	90
0	60	0	-90
42.63	0	0	90
0	10	0	-90
42.804	0	0	90
0	90	0	-90
0	0	0	90

b)

Figure 2. (a) DH coordinate frames for a single limb and (b) table for complete human

image-guided surgery is a natural solution.

Magnetic resonance imaging (MRI) provides excellent soft tissue discrimination and a well-defined 3D coordinate reference system. An intra-operative MR scanner (Signa SP/i, GE Medical Systems, Milwaukee, WI, 0.5 Tesla) has been specifically designed to bring the power of MRI to the operating theatre, Figure 1. It has a pair of parallel facing donut-shaped magnets, with an air gap of 560 mm. Two surgeons can stand in the gap to access the patient. In the last ten years, Brigham and Women's Hospital (Boston, MA), our collaborator, has recorded more than 500 cases using the intra-operative MR scanner.

In this paper, we demonstrate the type systnesis and the optimal dimensional design of a new MRI compatible surgical manipulator – MR SAM. The goal of our robot assist system is to enhance the surgeon's performance by accurate mechanics and numerical control, not to eject him or her from the surgical field. Therefore, the system must co-exist and co-operate with the surgeon. The system will actively navigate a small tool, such as a catheter needle, with “pin-point” accuracy, under intra-operative MR guidance. Intra-operative images will serve as the source of trajectory revision.

2 Work cell model

A *work cell*, in industrial robotics terms, is the area surrounding the robot during normal operation. This includes parts handling equipment, any obstacles in the work cell, and the parts on which the robot operates [Nof, 1999]. The marriage of industrial robotics and medical operations is somewhat contradictory because many standard practices for industrial robot work cell design must be ignored for this application. For example, it is standard practice to completely remove the human operator from the robot’s operational area and devise safeguards to ensure that a human, or other foreign object, does not physically interfere with the robot. This is inapplicable in medical robotics because the part on which the robot operates is a *human*.

2.1 Operating theatre

Images and information concerning the MR operating theatre were gathered during a visit to the Surgical Planning Laboratory (SPL) at Brigham and Women’s Hospital. The centre of the work cell, at the SPL, is a GE Signa 1.5 Tesla MR scanner. The scanner is capable of imaging a 30 cm diameter sphere at 1 mm resolution. Dedicated technicians control the scanner and imaging from a control booth adjacent to the operating theatre. From the control booth, the MR scanner and surgeons are visible. Communication between surgeons and the control room is accomplished via a two-way microphone and speaker set-up. A CAD model of proper scale was drawn in Solid Edge to capture the layout of the operating theatre, Figure 1b.

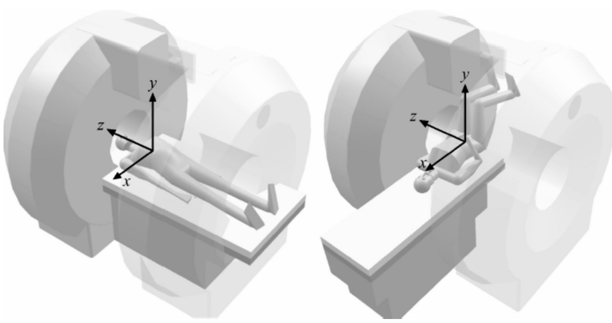
2.2 Human

A human model was created in Solid Edge to serve as a reference for the patient, surgeons and personnel [Roche, 2003; Petitt, 2004]. The limb segments are of proper proportions and the model can be moved and animated with the help of Excel. The data for the body proportions, total body height and range of motion was compiled from [Winter, 1990; Grandjean, 1980; Eastman Kodak, 1983]. The Denavit-Hartenberg convention [Denavit and Hartenberg, 1955] was used to model each limb because of the serial arrangement of human extremities. The co-ordinate frame definitions are shown in Figure 2 along with the Excel worksheet that is linked to the Solid Edge assembly document.

Two positions common for a patient are shown in Figure 3.

3 Design Specification

The purpose of the design specification is two-fold, first it serves as a method to define the constraints and objectives for the design, second it helps solidify the problem formulation. The design specification for an MR compatible SAM is contained in Table 1 (based on [Pugh, 1991]) and Table 2 (based on [Nof, 1999]).



a) b)

Figure 3. Two positions of the patient in open MRI

Table 1. Specifications for MR compatible SAM (1)

Geometry	Serial, parallel, or hybrid structure.
Kinematics	5-6 degrees of freedom (3 translation, 2-3 rotations) Rotation greater than +/- 20 degrees
Forces	Surgeon applied force Reactive forces from patient 20 kg load maximum
Energy	Supplied via electrical or pneumatic supply
Material	All materials must not be magnetic.
Signals	Measurement devices must be outside of imaging volume.
Safety	Must be easy to operate Must provide both mechanical and software fail-safe measures Must be MR compatible
Ergonomics	Forces required by finger pinch no greater than 45 N and should be below 30 N for repetitive work. Power grip not greater than 225 N, no more than 144 N for repetitive work
Production	1-2 systems, produced in-house
Quality Control	N/A
Assembly	In-house
Transport	N/A
Operation	**N/A**
Maintenance	Once a month
Costs	Manufacturing cost, development cost \$100,000 US. Break-even point, trade-off \$100,000 US. Delivery time 2 years. Quantity 1 - 5 total
Schedules	Design completed in two years

The imaging volume is a sphere 30 cm in diameter – approximately the abdomen diameter of an average male. The tool tip resides within the imaging volume during an MR assisted operation. The target volume diameter for most surgical procedures is much smaller than the imaging volume diameter, about 10 cm at maximum. [Kosugi et al., 1998] lists the tumour sizes for 13 craniotomies performed with their navigation system. For each case, the tumour size was less than 5cm^3 and the average size was approximately 2.5cm^3. A 10 cm diameter sphere at the origin of the world coordinate system is referred to as the *precision zone*, while the 30 cm imaging volume is referred to as the *imaging zone*, Figure 4. The resolution of the MR SAM is specified to be 1 mm, or less, inside the precision zone. The desired operating velocity of a surgical tool is approximately 10 mm/s with a maximum operating velocity of 50 mm/s. This speed requirement is much slower than conventional industrial robots. The relatively slow velocity is desirable because if an error occurs, the personnel operating the robot will have sufficient time to take corrective action. The current means of obtaining the tool position is a six dimensional tracking system integrated into the scanner [Chinzei and Miller, 2001].

Table 2. Specifications for MR compatible SAM (2)

Load Capacity	Weight of handled objects and end-effector Less than 5 kg. Load history Variable
Handled Objects and Tools	Dimensions of objects: long cylinders (needles) 190 mm x 8 mm diameter. Tool purpose: laser pointer, biopsy catheter, brachytherapy needle, endoscope tool/robot interface
Task Characteris-tics	Object/part presentation: presented by human Accessibility of objects parts: patient lies in front of robot Fixing and positioning: positioning from optical tracker Velocity 50 mm/sec maximum, 10 mm/sec nominal
Accuracy	Resolution +/- 1 mm Repeatability Unknown Path accuracy Unknown
Environmen-tal Conditions	Quantifiable Parameters: operates in 0.5 Tesla magnetic field at 21 MHz Sterile environment Non-quantifiable parameters: dynamic work environment
Repair/ Maintenance	Installation: installed before operation by trained personnel Removed after operation is completed Programming: firmware motion control Maintenance tasks and maintenance cycles unknown
Flexibility	Work cell integration: must integrate with the MRI machine Error handling, diagnosis: must have fault tolerant aspects Cooperation with peripheral devices: dedicated computer control

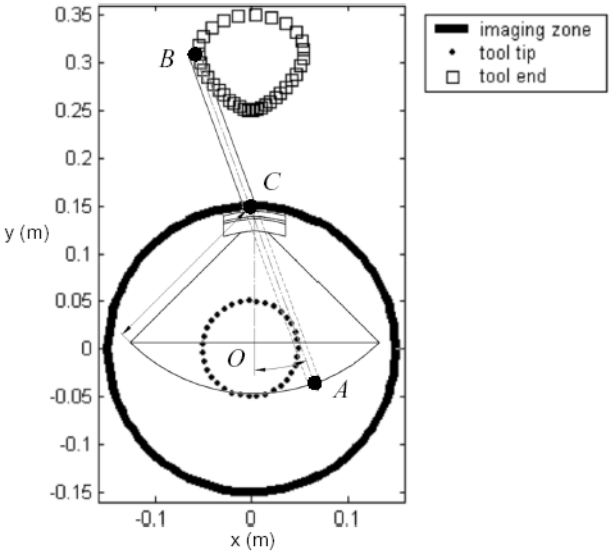


Figure 4. Imaging and precision zones

MR compatibility requirements of mechatronic devices were given in detail in [Schenck, 1996; Shellock, 1998] as well as in our previous work [Chinzei and Miller, 2001].

4 Optimal design process

4.1 Robot placement

A convenient location for base placement is above the surgeon. This area was used in the robot described in [Chinzei and Miller, 2001]. Another possible location for the base is inside the MR bore cavity, above the patient, Figure 5. This has two primary advantages over locating the base above the surgeon. First, the probability of collision with the surgeon is reduced because the robot body does not pass over the surgeon. Second, if the robot is designed to be placed inside the bore, then its application is not limited to open MRI and it could allow tool manipulation while a patient is lying in a closed MR scanner. The placement of the robot base also affects the quality of the MR image. The effects of linear ball screws made from non-magnetic materials were tested at distances of 24, 33 and 52 cm [Chinzei et al., 1999]. The tests showed no degradation in image quality, therefore the base of the robot should be at least 24 cm from the centre of the imaging zone.

4.2 Type selection

A fully-parallel mechanism was chosen for the MR SAM design investigated. The reasons for this are:
- The precision workspace of MR SAM is relatively small (< 10 cm^3).
- High angular resolution is required (< 0.5°).
- The actuation devices can reside on the base, away (> 24 cm) from the imaging volume.
- Closed-form inverse kinematic equations are easily derived for parallel robots.

4.2.1 Mobility analysis

The design specification states at least five degrees-of-freedom are needed for controlling minimally invasive surgical tools. [Merlet, 2000] demonstrated that it was not possible to construct a symmetric, fully-parallel robot with a mobility of four or five, therefore only designs with six degrees-of-freedom are feasible for the MR SAM.

If each leg is composed of two links and is actuated by a single degree of freedom device, then including the tool and base, a generic fully parallel six degree-of-freedom robot will consist of fourteen links.

The actuators must be fixed to the base, since this was the justification for choosing the parallel type. Linear guides driven ultrasonic motors were demonstrated to be MR compatible [Chinzei et al., 1999] and are used in the current MR compatible robot at the Surgical Planning Laboratory. Sensors for linear actuators can be obtained with very high resolution (0.0001 mm) for reasonable stroke lengths (>0.5 m). For these reasons, prismatic joints were chosen as the method of actuation in the kinematic model.

Mobility analysis is conducted using the Grubler-Kutzbach formula:

$$M = 6(nlinks - 1) - 5f1 - 4f2 - 3f3 - 2f4 - 1f5 \quad (1)$$

where: M is mobility and fr is the number of kinematic pairs having r degrees of freedom.

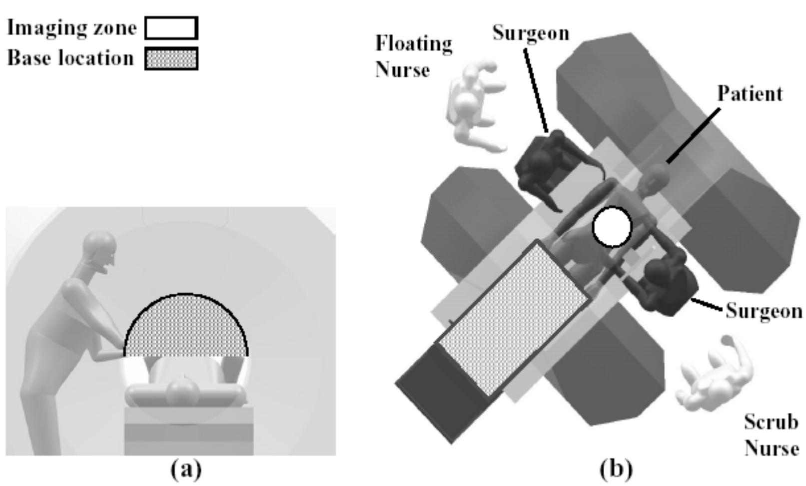


Figure 5. (a) Front and (b) top view with in-bore robot location

Substituting *nlinks* = 14 and accounting for six single-degree-of-freedom kinematic pairs (*f*1) in Grubler-Kutzbach formula (1) allows the remaining possible joint combinations for the legs to be identified:

$$6 = 6(14-1) - 5*(6+n1) - 4f2 - 3f3 - 2f4 - 1f5 \quad (2)$$

where *n1* is the number of passive single DOF kinematic pairs in legs. A symmetric fully parallel robot has identical joint arrangements for each leg, thus the following mobility criterion must be satisfied:

$$42/6 = (5n1 + 4f2 + 3f3 + 2f4 + 1f5)/6 \quad (3)$$

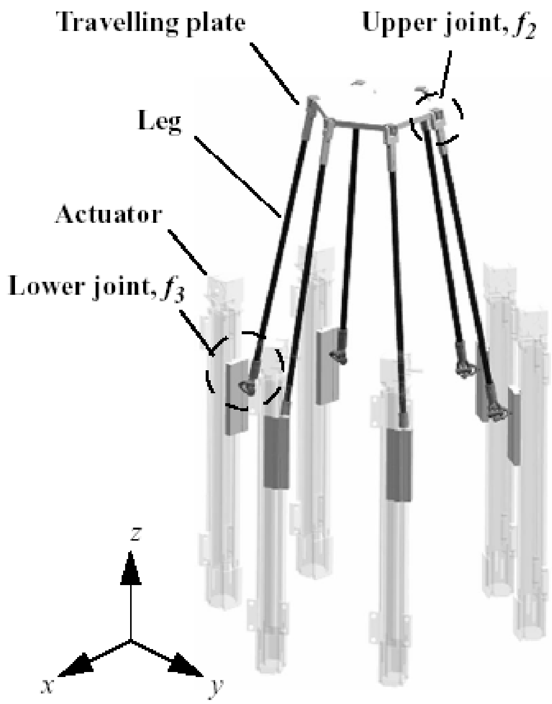


Figure 6. PSUx6 CAD model

There are a number of solutions to (3), but *f*4 and *f*5 joints are difficult to physically construct, so the most appealing is the use of a *f*2 and *f*3 passive joint combinations. If only *f*2 and *f*3 joints are used, then each leg must contain one *f*2 joint and one *f*3 joint. Type *f*2 and *f*3 joints are commonly manufactured and sold as universal and ball joints, respectively. This results in a PSUx6 configuration, Figure 6 and 7.

4.3 Dimensional synthesis

In order to conduct optimal dimensional design of the manipulator it was necessary to develop two new design tools: the end effector orientation visualisation tool based on colour spaces [Petitt and Miller, 2003]; and an evolutionary algorithm for workspace optimisation [Petitt and Miller, 2004]. Robot dimensions were optimised with an objective to maximise manipulability in the precision zone. The methods used to analyse manipulability are described in [Stock and Miller, 2003; Miller, 2004]. The workspace was analysed using methods taken from [Miller, 2002]. The results of the optimal design process are given in Table 3 and Figure 8.

Table 3. Optimal Geometry for PSUx6

Dimension	Normalised value (devided by the robot base radius)	Scaled value
α (see Figure 9)	Π/12	Π/12
γ (see Figure 9)	13Π/12	13Π/12
Radius of traveling plate	0.3	6.0 cm
Leg lengths: Leq 1 and 2 Leq 3 and 4 Leq 5 and 6	 2.5 2.5 2.4	 50.0 cm 50.0 cm 48.0 cm
Base radius	1	20 cm
Actuator stroke	>2.5	>50 cm
Minimum joint sensing resolution	3.0×10^{-3} mm	

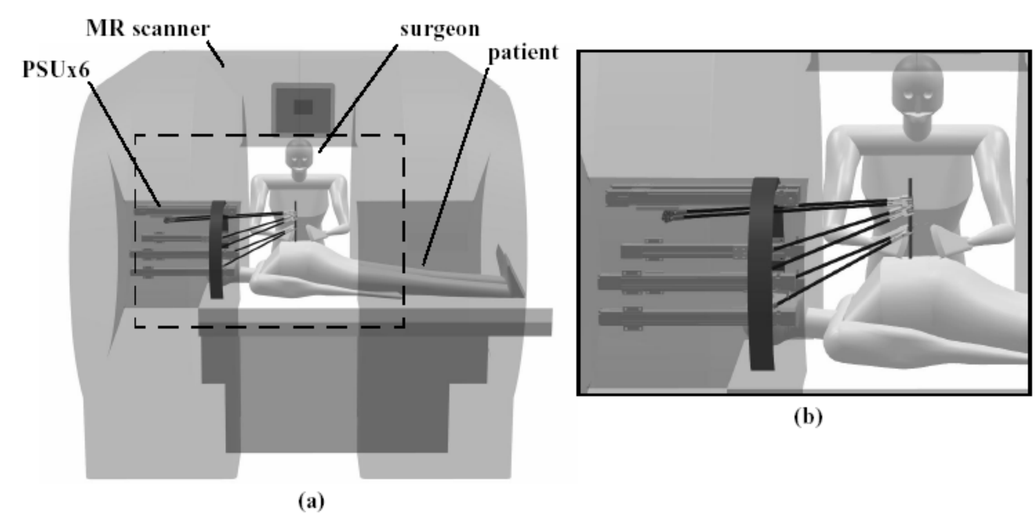


Figure 7. (a) PSUx6 in MR scanner with surgeon and patient and (b) close view

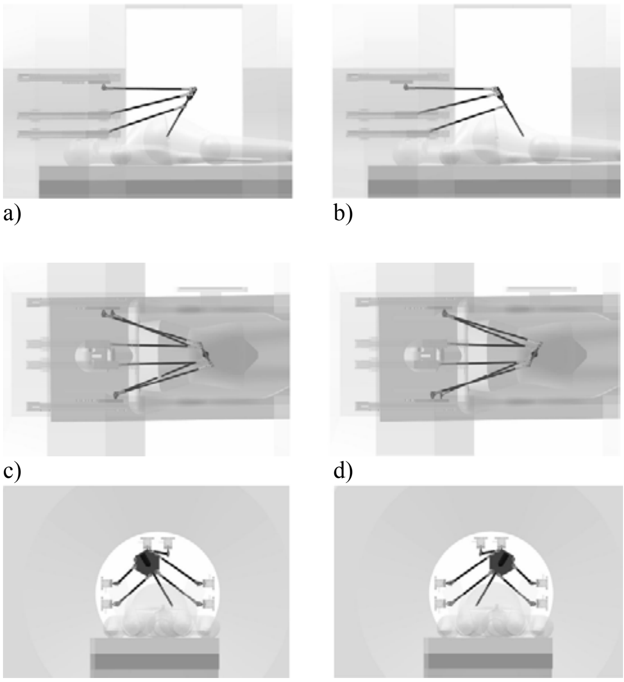


Figure 8. Final design of MR SAM with:
(a) 30° rotation and (b) -30° rotation about x-axis
(c) 30° rotation and (d) -30° rotation about y-axis
(e) 30° rotation and (f) -30° rotation about z-axis

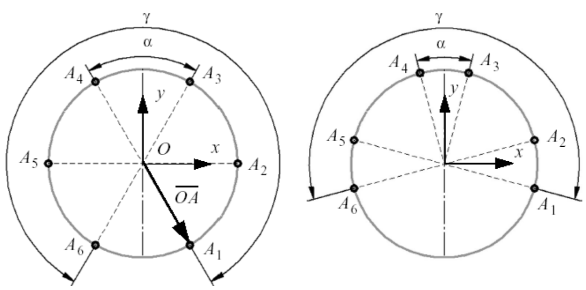


Figure 9. Actuator layout for (a) symmetric and (b) semi-symmetric designs

4 Conclusions

We have presented a design of MR SAM - the PSUx6 robot, optimised for the application to surgical assistance. The additional constraint on the design was that the robot must be MR safe. This required placing the actuated joints and sensors outside of the imaging volume of the MR scanner. A parallel robot topology, characterised by multiple links connecting a tool to a fixed base, was chosen as the mechanism type. The advantage of the parallel architecture is that the actuated joints are placed at the base, at a distance that has been shown to be MR safe for other MR compatible robots. The robot is actuated by prismatic joints, which were used in a previous MR robot and proven to be MR compatible. Using the software tools described in [Petitt and Miller, 2003; Petitt and Miller, 2004], manipulability analysis methods described in [Stock and Miller, 2003; Miller, 2004], and workspace analysis methods taken from [Miller, 2002] the geometric variables were optimised to maximise the manipulability of the tool within a dextrous task volume. The prototype of the devise will be constructed in the collaboration with Surgical Assist Technology Group of AIST, Japan.

Acknowledgements

This research has led to the submission of MSc thesis [Petitt, 2004]. The financial support of The UWA's IPRS programme is gratefully acknowledged.

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