Synthesis and Workspace Study of Endoscopic Extenders with Flexible Stem

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Abstract

This paper studies and formulates the *workspace* of laparoscopic extenders(e.g. graspers, needle drivers, scissors etc.)with flexible stems, that provide additional DOF, and dexterity at the surgical sight. Optimization techniques are used to synthesis the designs of flexible stems. The *dexterous workspace* is determined for 3 different types of designs. By defining a new *dexterity measure* the number of joints for each design is optimized. Also, the three designs are compared with each other and the most dexterous designs are determined.

1 Introduction

Endoscopic surgery is a less invasive method of surgery as compared to the open surgery, and has many advantages such as;

- Shorter recovery time.
- Lower risk of infection.

Figure 1: Endoscopic Surgery.

- Less pain/ trauma for the patient.
- Reduction in hospital stay/cost.

On the other hand, indirect vision, limited hand movement and lack of force sensing, combined with the tiring posture of holding long tools makes it a very difficult task for the surgeon to perform[Tendick, *et al.*, 93][Faraz, *et al.*, June, 95]. Consequently of these difficulties, the surgeon has a fraction of *dexterity* and *sensing* of that of the open surgery. This is specially the case in laparoscopic surgery which is a specific branch of endoscopic surgery, and is performed on the abdominal part of body (Fig.1).

There have been some developments of new endoscopic surgical tools, vision systems and a few robotic assisting devices[Rininsland, 93][Melzer, 93][Neisius,*et al.*, 94][Taylor,*et al.*, 95]. However there exists a great demand for research in the development of mechanisms and systems to answer some of the basic needs of surgeons.

In the laparoscopic surgery(as a specific branch of endoscopic surgery), tools and the endoscope are passed through the incision points and trocars on the abdominal wall, so they can reach the surgical site. In laparoscopy the abdominal wall, as a kinematic constraint, acts as a pivoting point (it permits 3 DOF of rotary movement around the incision point, as well as one translational DOF). This spherical movement of tools by the surgeon is the *inherent* and *primary* constraint of laparoscopic surgery, and should be considered prior to any analysis and design of tools and systems. The dexterity problems associated with laparoscopic surgery arises from the fact that the present rigid stem tools can approach the surgical site with some fix orientation (determined by the connecting line between the position of surgical site and the port of entry). Lack of 2 DOF at the tool's stem to orient the tools tip to the desired orientation near the surgical site, prevents the surgeon to have the required dexterity and agility. By adding rotary joints on the stem the required flexibility in orienting the tool can be achieved. However, the challenge is to synthesis the flexible stem so that it can provide the *required range of rotation* over the *largest* workspace. This paper studies workspace of flexible laparoscopic extenders to devise a criterion to determine the optimum type of design.

In the next section, as part of the design synthesis, alternative designs of flexible stems are described. In section 3 and 4 workspace study, as well as optimization of flexible stems are performed. The results of optimization are used to evaluate the different types of flexible stem designs in section 5.

2 Synthesis of Flexible Laparoscopic Extenders

For synthesis of the flexible stem, first we need to know what type of joint provides the required range of rotary motion and DOF. This is related to the *type synthesis* of the design. In general there are two classes of rotary joints a) revolute joint(with 1 DOF), b) spherical joint(with 2 DOF). The challenge and difficulty lies in design of these joints on a stem which has a diameter of only 10 mm and operates deep inside the body. The mechanical design still should provide some room for the linkages and connectors to pass through the joint(s) to the other moving elements and sensors at the end of the stem. However, there could be many variations in the design, here only three potential designs are studied where 2 are revolute and 1 spherical type as followings:

Type.1- 4 bar linkage design

This design is based on 4 bar linkage mechanism, that actuates the single revolute joint on the stem(Fig.2). This can provide a simple joint mechanism with 1 DOF. The difficulty is in designing a single revolute joint that can provide all the wide range of rotation(e.g. 0 to 120°).

Type.2- Lead screw multi-revolute joints design

This design consists of several revolute joints which are actuated by left/right handed lead screws that are connected by flexible couplings together in series (Fig.3). The input rotation of the first lead screw actuates all the joints to the same angle (Maximum of 45° each) as 1 DOF. The disadvantage of this design could be the relatively high number of moving parts.

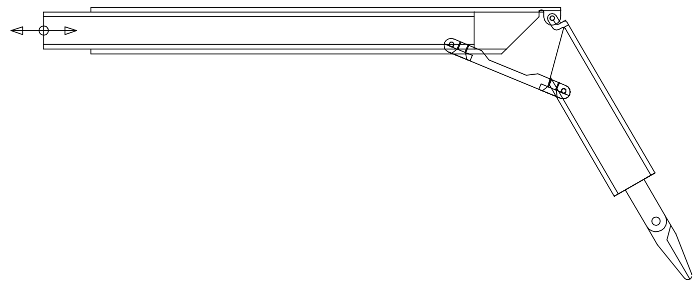

Figure 2: 4 Bar Linkage actuated Single joint design

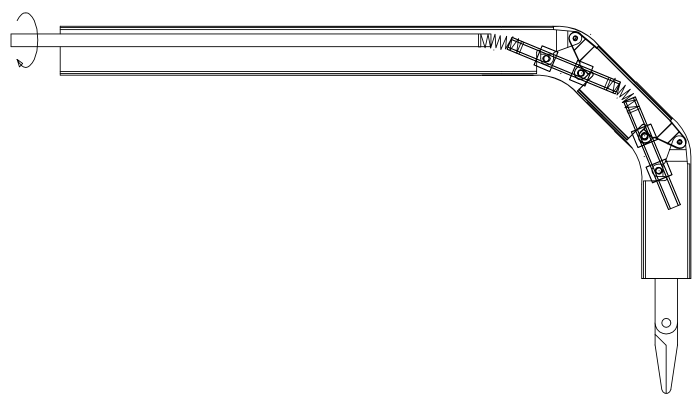

Figure 3: Lead screw actuated multi-revolute joints design

Figure 4: Tendon actuated multi-spherical joints design

Type.3- Tendon actuated multi-spherical joints design

The actuation of a series of spherical joints by tendons can provide 2 DOF(Fig.4). The tendons movements can be generated by a master mechanism at the handle which can be actuated by the surgeon's fingers. The difficulty lies in friction modeling [Faraz, *etal.* May,95][Faraz, *etal.* Submitted July,95] of the spherical joints and control of tension in tendons for moving and locking the joints.

Finally, we need to know what number of joints is optimum for multi-joints designs(e.g. design 2, and 3). This is related to the *number synthesis* of the design[Shigley,*etal.*, 1981] which is a main goal of this study.

3 Laparoscopic Workspace Formulation

For any robotic arm or manipulator being able to reach a "prescribed workspace" is an important and essential requirement, which should be studied from the early stage of design. The classification of workspace by Park, 1995, into two classes of a) *Reachable Workspace*, and b) *Dexterous Workspace* are defined as: "Given a special point P attached to a manipulator's end effector, such as the point of intersection of the wrist axes, the *reachable workspace* is defined to be the set of points in physical space that can be reached by point P. The *dexterous space* on the other hand is the set of points that can be reached by P with arbitrary orientation of the end-effector." This classification is very useful and subsequently applied in our specific study of flexible stems.

Basically in laparoscopy due to kinematic constraints at the incision point, the

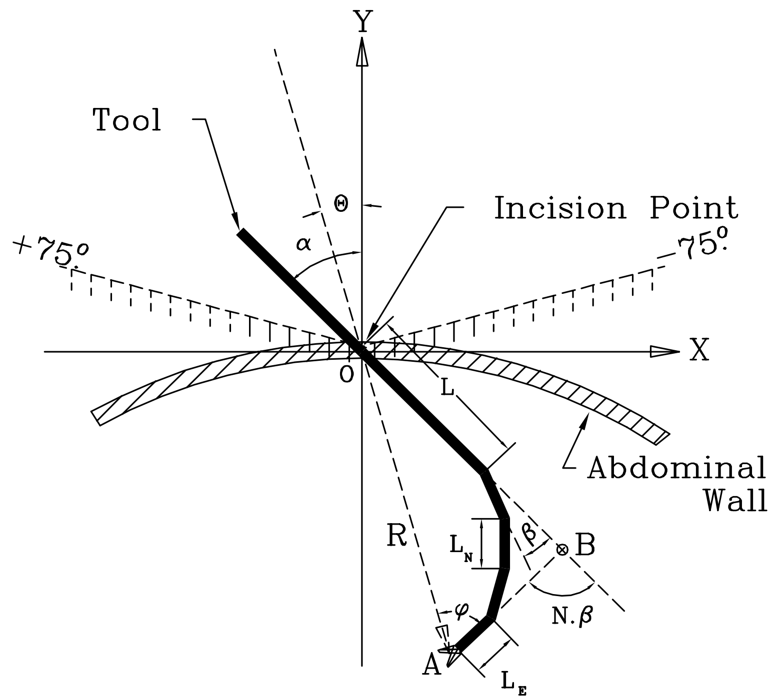

Figure 5: Endoscopic workspace of a flexible stem tool.

movement of tool is limited to rotational movements around the incision point and axial movement in and out of abdomen. The flexible stem can in general be considered generally as a long stem with N joints where intermediate linkages have size L_N and the end link with grasper has size L_E(Fig.5). In other words (in a 2 dimensional plane, passing though the incision point), to reach a point in the workspace with coordinates $[R, \Theta]$, and orientation φ, the stem has to deflect to angle α , and penetrate length L (shown in Fig.5) beyond the last joint.

The variables of this formulation are:

a) Workspace Variables: R, Θ, φ (Fig.5)

b) Design Variables: L_N, L_E, β, N.

Where N is the number of joints, β is the deflecting angle of each joint, L_N is the length of links connecting joints, and L_E is the length of end linkage with grasper.

There are various classes of motion constraints such as a) workspace, b) design limits of different flexible stem types, as well as geometric constraints which are described as followings:

3.1 Inequality Constraints:

Workspace: $80 \leq R \leq 280mm$; depth penetration range of surgical site for laparoscopic procedures.

$\alpha \leq 75°$; flexibility range of abdominal wall.

Design: $L_E \geq l_e$; minimum size of intermediate links.

$L_N \geq l_n$; minimum size of end link.

$\beta \leq \beta_{max}$; maximum range of joints deflection.

$N \leq n$; feasible range of joints number.

Based on the type of design the parameters β_{max}, l_n, l_e, and n are the limiting values of variables β, L_N, L_E, and N. For the three types of designs considered here, these parameters are given in Table 1:

Design	β_{max}	l_n	l_e	n
1	90.	0.	70.	1
2	45.	28.	60.	2-4
3	30.	10.	50.	3-5

Table 1: The design variables of 3 types of flexible stem.

3.2 Equality Constraints:

For a flexible stem to reach point A in the workspace with coordinates $[R, \Theta]$ and orientation φ, each joint has to rotate by an angle β and penetrate up to length L distance beyond last joint(Fig.5). In this respect, the kinematic model of the flexible stem as a multi-body system results in the following geometric equality constraints:

$$L \sin \alpha + L_N[\sin(\alpha - \beta) + ... + \sin(\alpha - (N-1)\beta)] + L_E \sin(\alpha - N\beta) = R \sin \Theta$$

$$L \cos \alpha + L_N[\cos(\alpha - \beta) + ... + \cos(\alpha - (N-1)\beta)] + L_E \cos(\alpha - N\beta) = R \cos \Theta$$

Or in the following form :

$$\begin{bmatrix} L \\ L_N \\ L_E \end{bmatrix}^T \begin{bmatrix} \sin \alpha & \cos \alpha \\ \sum_{i=1}^{N-1} \sin(\alpha - i\beta) & \sum_{i=1}^{N-1} \cos(\alpha - i\beta) \\ \sin(\alpha - N\beta) & \cos(\alpha - N\beta) \end{bmatrix} = R \begin{bmatrix} \sin \Theta \\ \cos \Theta \end{bmatrix}^T$$

3.3 Objective Function:

In this planar formulation of laparoscopic workspace(Fig.5), there are three workspace variables(or coordinates)$[R, \Theta, \varphi]$. The objective is to find the maximum approach angle φ for any given point in the space$[R, \Theta]$. This is treated as an optimization problem where the objective function is to maximize φ, for different values of R, and Θ. The objective function can be formulated by geometry of the triangle OAB(Fig 5), where the angle $N\beta = \varphi + \alpha$, which can be rearranged as:

$$\textbf{Maximize: } \varphi = N\beta + \Theta - \alpha$$

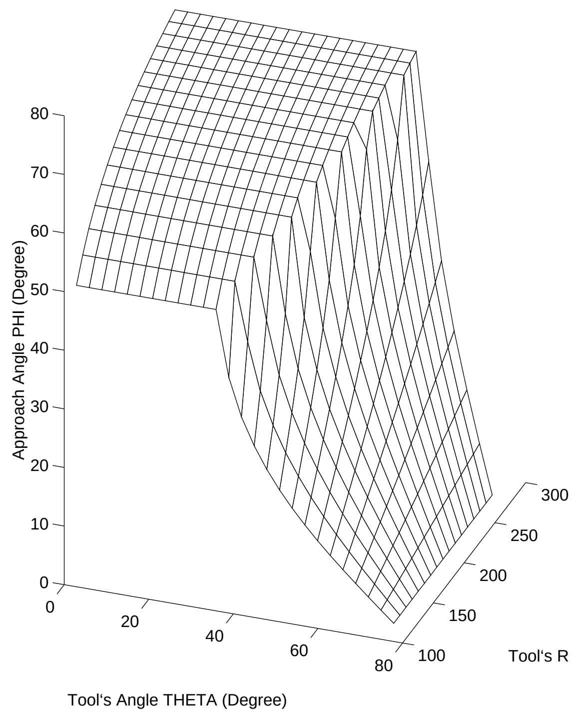

Figure 6: The workspace of design 1 .

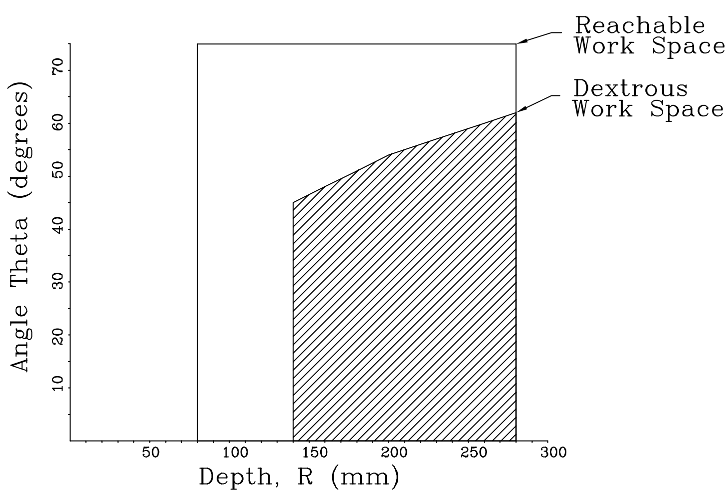

Figure 7: Design 1 with 1 joint.

4 Results

The proposed formulation has been solved for 546 points of workspace(i.e. a 26×21 mesh of $3°$ increments in Θ direction, and $10mm$ in R direction). For design 1, φ vs. Θ and R is shown in Fig.6 . This illustrates that φ increases as R increases(this is expected since the tool would have more room for bending as it penetrates deeper). However, as Θ increases, φ remains constant first, and then it deceases sharply as soon as the base of stem reaches the angular limit of α(i.e. $75°$).

Same trend for φ is observed for all three designs with different ranges and maximum limits of φ. In some cases, the range of φ is from 0 to maximum value of $120°$ for some designs. However a flexible stem could be considered dexterous only if it can approach a given coordinates$[R, \Theta]$ with a minimum approach angle φ_{min} in the range of $30 - 90°$, depending on the required level of dexterity this limit could vary in that range(i.e. $30 - 90°$). The average value of $\varphi_{min} = 60°$ is chosen to be the range for the minimum approach angle of the tool to a given coordinates$[R, \Theta]$. Therefore by choosing the minimum limit of $60°$ for angle φ, in Fig.6, only the portion of workspace which is above the limit (i.e. $\varphi \geq 60°$) can be considered as the *dexterous workspace*. The top view of this dexterous workspace(i.e. R vs. Θ) is shown in Fig.7 in comparison to the total reachable workspace.

Same procedure is performed for design 2 with 2,3, and 4 joints, and for design 3 with 3,4, and 5 joints as shown in Fig.8, and 9. This provides the basis for comparison of their dexterous workspace with different number of joints as the criterion for number synthesis of these designs.

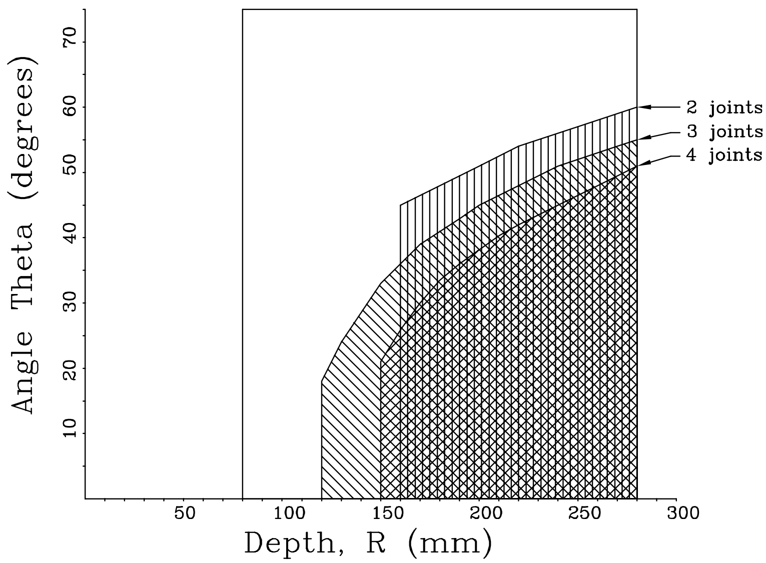

Figure 8: Design 2 with 2, 3, 4 joints.

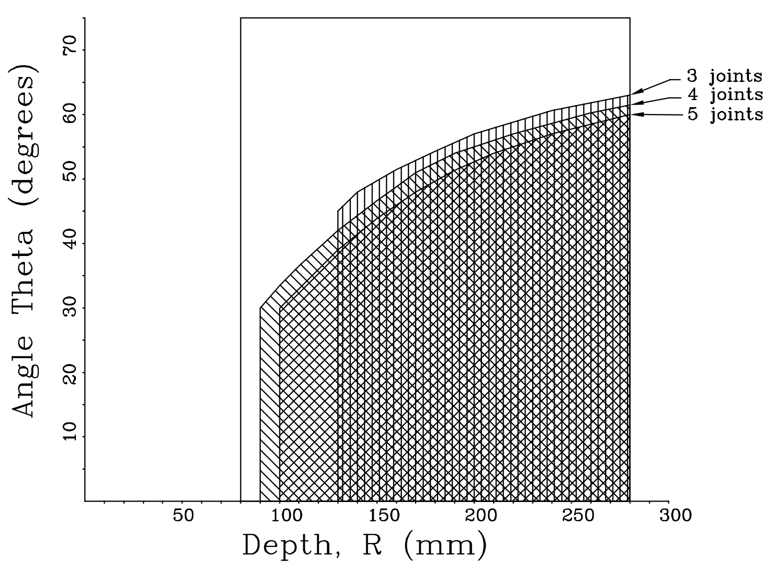

Figure 9: Design 2 with 3, 4, 5 joints.

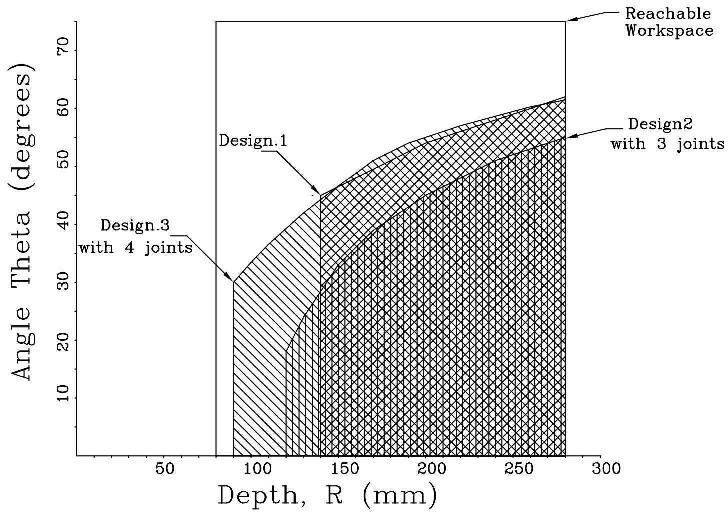

Figure 10: Dexterous workspace of design 1, 2, 3.

5 Discussions and Conclusions

In order to compare the performance of multi-body systems locally (i.e. at some specific location) or globally (i.e. in the entire workspace), performance measures are used in the literature to quantify different performance characteristics of the system. For example, Yoshikawa, 1985, introduced $W = \sqrt{det(JJ^T)}$ (where J is the Jacobian of the manipulator) as a local manipulability measure for comparing manipulating forces at different directions, or Doel and Pai, 1996, have defined several new measures for inertia, and redundancy of multi-body systems.

In this work, to be able to compare dexterous workspaces of different designs with the reachable workspace as well as comparison of the designs with respect to each other, a new *Dexterity Measure* is defined as the ratio of areas that dexterous and reachable workspaces occupy(Fig.7):

$$DexterityMeasure = \frac{DexterousWorkspaceArea}{ReachableWorkspaceArea}$$

For example, the ratio of the shaded area to the rectangular area is the dexterity measure of design 1 (for the planar workspace shown in Fig.7). The ratio is dimension less and always between 0 and 1, since the dexterous workspace is always a subset of reachable space. This provides a global dexterity measure that indicates what percentage of the reachable workspace is dexterous. Furthermore, since the reachable workspace is the same for all three types(Fig.10), the ratio could be used for comparison of their dexterity with each other, as shown in the following table:

Design	1	2			3		
Joints, N	1	2	3	4	3	4	5
Dexterity Measure	**51%**	43%	**45%**	34%	56%	**64%**	59%

Table 2: Dexterity measures of design 1, 2, and 3.

Based on the calculated dexterity measures in Table 2, and Fig.s 8, 9, and 10, following conclusions regarding different designs could be made:

- Design 2 has the highest dexterity with 3 joints.
- Design 3 has the highest dexterity with 4 joints.
- Design 3 is the most dextrous compared to other two designs.
- For relatively deeper operating sites(where $R > 130mm$), design 1 provides same dexterity as design 3(Fig.10), while in comparison with design 3, it is much simpler in design and easier to actuate.

- Design 2 does not have any dexterity advantage compared to other designs.

Based on the approach of this work, following general conclusions could also be made:

- This formulation can be used for any manipulator or robot with the same configuration (as the endoscopic flexible extenders), to obtain its dexterous workspace.

- The global dexterity measure defined in this work is a simple but effective way to compare dexterous workspace of different manipulators and robots.

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