TECHNICAL UNIVERSITY OF CLUJ-NAPOCA

ACTA TECHNICA NAPOCENSIS

Series: Applied Mathematics and Mechanics
Vol. 54, Issue II, 2011

DESIGN AND ANALYSIS OF AN ORIENTATION MODULE FOR INSTRUMENT USED IN MINIMALLY INVASIVE PROCEDURES

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Abstract: *The design and analysis of a module for the orientation of the instrument tip in minimally invasive surgeries are presented in the paper. Some aspects related to its design and modularity point out the advantages of the proposed solution. A comparison study is performed assessing the workspaces of classical instruments and ones that use the orientation module pointing out the advantages of the proposed solution.*
Key words: *design, modularity, minimally invasive surgery, custom solutions, innovative development*

1. INTRODUCTION

„*Coninuetur remedia*" – *Let the medicine be continued.*

Medicine, and especially its invasive branch, surgery, have known a continuous evolution animated by the ultimate goal of improving the life quality of humankind. In surgery, the latest revolution began 25 years ago, when it appeared, for the first time the concept of minimally invasive surgery (MIS), and since then reached the present stage of robotic assisted minimally invasive procedures and the newer NOTES (Natural Orifice Transluminal Endoscopic Surgery) and SILS (Single-Incision Laparoscopic Surgery). While the real benefits of NOTES are somehow doubtful as shown in [1], [2], SILS represents a real benefit for patients suitable for this procedure. Compared to classical laparoscopic or MIS procedures its benefits are: decreased pain, shorter recovery period (counted in hours), lower morbidity, reduced cost and superior cosmesis. Kamran, Patel and others [2] published a report where they analyzed several hundreds of cases before pointing out these advantages. However, SILS as the name suggests, means the introduction of all the surgical tools (camera, and instruments) through a narrow port of 15 – 20 mm, or the use of multilumen trocar forcing the surgeon to work in awkward positions, with crossing instruments etc. There are multiple technical challenges which the surgeon faces in SILS [3] and in order to overcome them and maximize the impact of the procedure special instruments have to be developed. On a global scale, there are only several solutions which propose articulated instruments: Read Hand (Novare Surgical Systems), Autonomy Laparo-Angle (Cambridge Endo) and Roticulator (Covidien).

Modularity, custom designed solution and reconfigurability are actual trends in many research fields as they provide with the same basic solution multiple solutions, customized and optimized on the specific application requirements.

The biggest challenge in the design of tools for minimally invasive procedures, equipments used inside the patient, is the size versus complexity. Nowadays the trend aims towards instruments of 10, 5 and 2 millimeters in which case adding a function to a classical instrument becomes a real challenge.

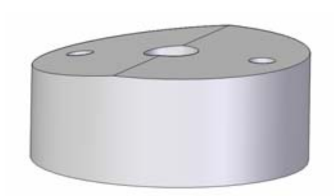
The paper proposes an innovative modular solution, which transforms any classical instrument in an articulated tool, and allows customization based on the procedure special needs. Besides that, it proposes the use of multiple curvatures (bends) which can prove very useful in MIS procedures for avoiding frontal objects, to allow lateral approach and in SILS to set the tips of the instruments apart.

The presented approach provides a construction which offers multiple solutions without the need of redesign.

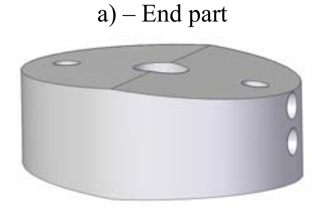
After a short introduction, the design of the orientation module is presented, followed by a study upon the benefits it provides, based on an analysis of its workspace, compared to a stiff classic instrument. In the last section some conclusions and future work will be presented.

2. DESIGN OF AN ORIENTATION MODULE FOR INSTRUMENT IN MIS

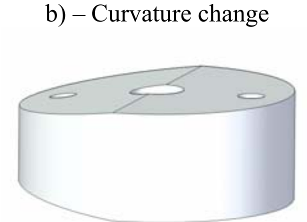
The modular approach proposes the use of 3 different elements which allow the setup of various configurations [4]. These three elements are: the end parts (the module extremities) the curvature change parts and the intermediary parts. The solution can be applied to any of the dimensional model of laparoscopic instruments (10, 5 and 2 mm in diameter) and allows the development of particular solutions, without the need of redesign. Figure 1 (a, b and c) presents these elements.



a) – End part



b) – Curvature change



c) – intermediary part

Fig.1 The components of the modular orientation tool

The dimensional parameters are generalized, as the user can select / set any desired values, the final number of elements being imposed by these parameters. Each module has two end parts positioned in the extremities of the module, a number of intermediary parts which depends on the desired curvature angle for each bend of the module and the inclination angle of the element surface. If more than a curvature is needed, the part presented in figure 1.b is used in order to achieve that. In this way using just three different elements theoretically any configuration can be achieved. In figure 2 such an example is illustrated, with a module having two curvatures, and a inclination angle of the element surface of $\alpha = 7.5^{\circ}$.

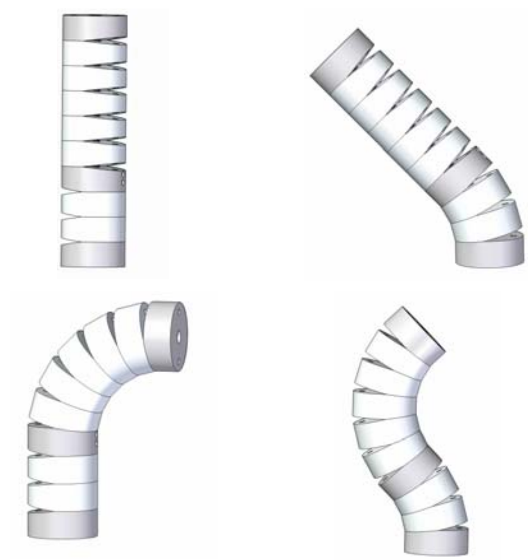


Fig. 2. Orientation module with two curvatures in different configurations

The orientation module in figure 2 has four possible configurations:

- straight position;
- first curvature bended;
- second curvature bended;
- both curvatures bended.

In this way, during the procedure the surgeon can select between a classical approach to an angular one, lateral one, the fourth configuration being of great help when he needs to avoid an obstacle. The bending / unbending of the module is achieved by wires which are passing through each element and are actuated by means of two wheels positioned near the instrument handle for easy access.

The length of the wires has to be determined in accordance with the dimensions of the module, number of elements and curvature. In order to establish some general calculation rules all the dimensions have been denoted a general formula being determined.

For the dimensional calculus the following geometrical parameters are considered:

- n – total number of elements;
- m, p – number of intermediary elements for each bend;
- α – the inclination angle of the surface of the elements;
- D – diameter of the elements;
- L – the thickness of the elements;
- D_0 – the diameter of the circle on which the leading holes are placed on;
- h – the height of the fixing holes for the wire end.

Knowing that:

$$n = m + p + 2_{ep} + 1_{cc} = m + p + 3 \tag{1}$$

Where:

- 2_{ep} represents the number on end parts (2);
- 1_{cc} represents the number on curvature change parts, which is 1 in this case.

The angles of the bends can be determined using the equations:

$$\varphi_1 = (m+1)\cdot 2\cdot\alpha$$
$$\varphi_2 = (p+1)\cdot 2\cdot\alpha \tag{2}$$

Considering that there is no slip of the wire on the driving wheel (which can be easily accomplished by proper selection of the wire, material and surface roughness of the wheel), in the straight position the lengths of the wire on each side of the module is equal. The following notations are used:

- l_{1i} - the length of the wire on the curvature side for the first bend (i - inside);
- l_{1o} - the length of the wire on the opposed curvature side for the first bend (o - outside);
- l_{2i} - the length of the wire on the curvature side for the second bend (i - inside);
- l_{2o} - the length of the wire on the opposed curvature side for the second bend (o - outside).

Without any simplification hypothesis or influence on the calculus accuracy, these lengths are measured from the first element onward.

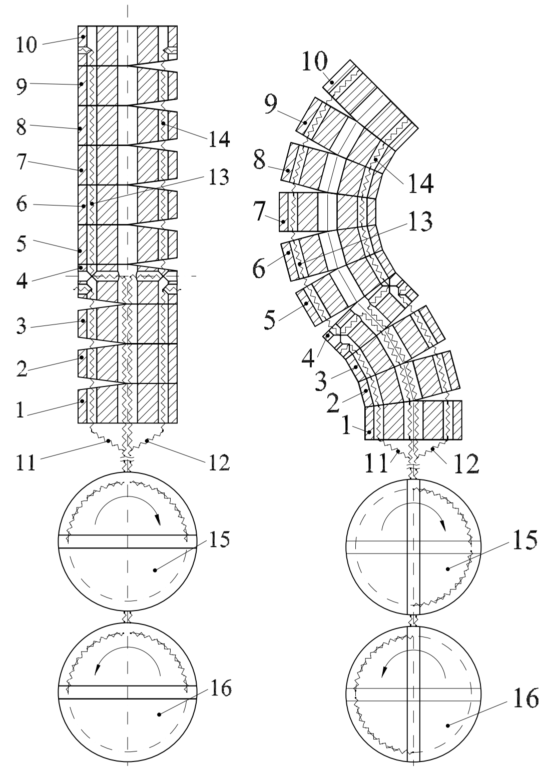


Fig. 3. Section view through the orientation module

The initial lengths of the wires can be calculated as follows:

$$l_{1i} = l_{1o} = L\cdot(m+1) + h + (D - D_0)$$
$$l_{2i} = l_{2o} = L\cdot(n-1) + h + (D - D_0) \tag{3}$$

The lengths of the wires when the module is actuated, and the bends achieved, results as follow:

$$l_{1i\_a} = L\cdot(m+1) + h + (D - D_0) - (m+1)\cdot D\cdot\sin(\alpha) =$$
$$= [L - D\cdot\sin(\alpha)]\cdot(m+1) + h + (D - D_0)$$
$$l_{1o\_a} = [L + D\cdot\sin(\alpha)]\cdot(m+1) + h + (D - D_0) \tag{4}$$

For the second curvature, the length of the inner and outer wire will be as follows:

$$l_{2i\_a} = L\cdot(n-1) + h + (D - D_0) - (p+1)\cdot D\cdot\sin(\alpha)$$
$$l_{2o\_a} = L\cdot(n-1) + h + (D - D_0) + (p+1)\cdot D\cdot\sin(\alpha) \tag{5}$$

From equations 3, 4 and 5 result that the wire length variation is equal on the inner and outer sides of the curvatures. Considering that each wheel will be rotated with half turn to achieve the bend, the diameter of the two wheels results as follows:

$$d_1 = \frac{4 \cdot (m+1) \cdot D \cdot \sin(\alpha)}{\pi} \quad d_2 = \frac{4 \cdot (p+1) \cdot D \cdot \sin(\alpha)}{\pi} \qquad (6)$$

3. WORKSPACE ANALYSIS

This analysis, implemented in Matlab [7] tries to determine the potential benefits of using this type of orientation module added to a classical rigid instrument in three different situations:

- touching/palpation – the instrument must be able to touch a given surface;
- grasping – the instrument must touch the surface under an angle of at least 45°;
- cutting – the instrument must touch the surface under an angle of at least 60°.

In [5] and [6] workspace analysis of surgical instruments has been thoroughly studied, pointing out several motion particularities:

- the instrument must pass always through a fixed point in space (the insertion point);
- the angle between a normal axis on the insertion surface and the instrument must net exceed 60°;
- denoting with A the outer extremity and with E the tip of the instrument the following restrictions apply [6]:

$$\overline{AB} \geq 50mm, \quad \overline{BE} \geq 80mm .$$

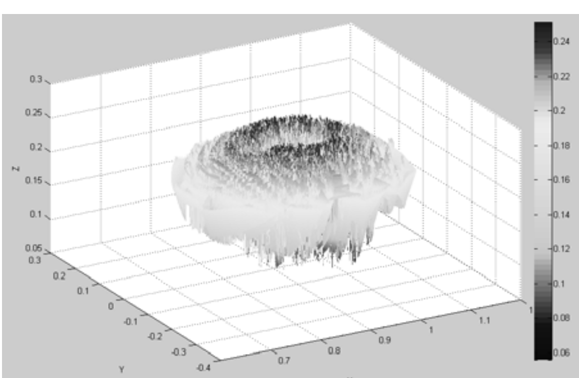


Fig.4. Total workspace of the instrument

If no other restrictions are applied, the total workspace of a classical instrument, referring to the first situation, touching/palpation is presented in figure 4. The equations used for the determination of instrument tip coordinates are:

$$\begin{aligned} e &= \sqrt{(X_A - X_B)^2 + (Y_A - Y_B)^2 + (Z_A - Z_B)^2} \\ \varphi &= a\tan 2\left(\sqrt{1 - \left(\frac{Z_A - Z_B}{e}\right)^2}, \frac{Z_A - Z_B}{e}\right) \\ \theta &= a\tan 2(Y_A - Y_B, X_A - X_B) \end{aligned} \qquad (9)$$

The coordinates of the instrument tip are:

$$\begin{cases} X_E = X_A - h \cdot \sin(\varphi) \cdot \cos(\theta) \\ Y_E = Y_A - h \cdot \sin(\varphi) \cdot \sin(\theta) \\ Z_E = Z_A - h \cdot \cos(\varphi) \end{cases} \qquad (10)$$

For the instrument with the orientation module, using the angles determined in eq.2 the equation results:

$$\begin{bmatrix} X_{E1,2} \\ Y_{E1,2} \\ Z_{E1,2} \end{bmatrix} = \begin{bmatrix} X_G \\ Y_G \\ Z_G \end{bmatrix} + [R] \cdot \begin{bmatrix} x_{E1,2} - x_E \\ y_{E1,2} - y_E \\ z_{E1,2} - z_E \end{bmatrix} \qquad (11)$$

where *[R]* - rotation matrix around the X axis, G the origin point for the orientation module and $E_{1,2}$ the instrument tip coordinates corresponding to the actuation of the first and second bend. In order to be able to make a comparison between the workspace of a classical instrument and one which has the orientation mechanism, a section in the workspace is considered, representing the two workspaces with different colors on the same figure. The areas of the two surfaces are then calculated and the gain determined. For the calculation, the following geometrical parameters are considered: instrument length $h = 350mm$, point B coordinates: $X_B = 950\ mm,\ Y_B = 0\ mm,$ and $Z_B = 300\ mm$, length of the orientation module $l = 50mm$. For the selected section plan, the following condition is imposed:

$$X_A = X_B \qquad (12)$$

The other two coordinates having the following value domains:

$$Y_B - h \le Y_A \le Y_B + h \qquad (13)$$
$$Z_B \le Z_A \le Z_B + h$$

In this particular case, the system (11) has the following solutions:

$$\begin{cases} X_{E1,2} = X_A \\ Y_{E1,2} = Y_A - \sin(\varphi)\cdot\left[(h-l) + l\cdot\sin(\varphi_{1,2})\right] \\ Z_{E1,2} = Z_A - l\cdot\cos(\varphi)\left[1-\cos(\varphi_{1,2})\right] \end{cases} \qquad (14)$$

For the first situation, namely touching/palpation, the analytical results are presented in figure 5; in this case, the result shows a gain of 12.24% in workspace volume.

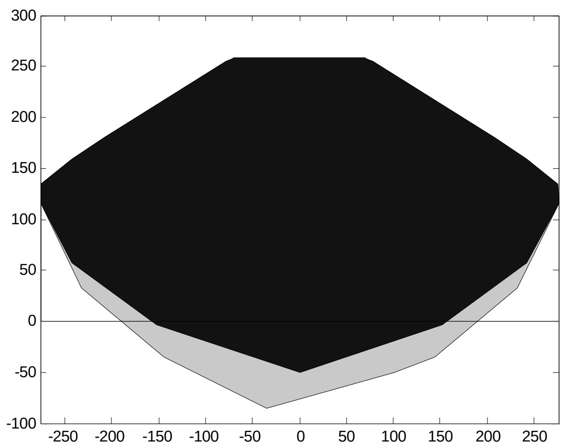


Fig. 5. Section view of workspace for an instrument with orientation module (light) and a classical one (dark)

The second situation, which refers to grasping, is presented in figure 6; in this case, the result shows a gain of 46.38% in workspace volume.

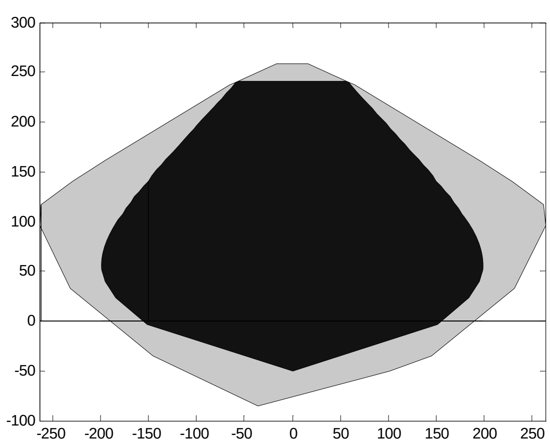


Fig. 6. Section view of workspace for an instrument with orientation module (light) and a classical one (dark)

The third situation, which refers to grasping, is presented in figure 7; in this case, the result shows a gain of 86.89% in workspace volume.

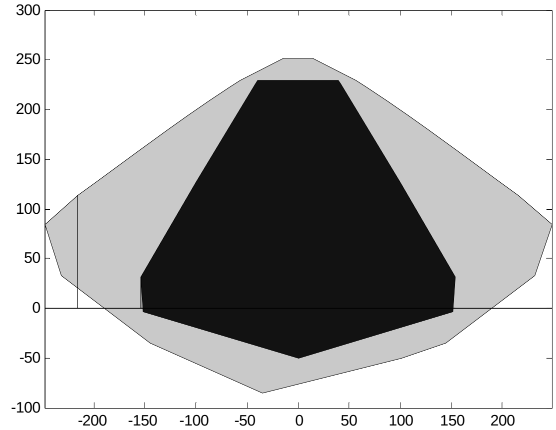


Fig. 7. Section view of workspace for an instrument with orientation module (light) and a classical one (dark)

Making a short analysis upon each of the three tasks subjected to analysis, one can easily see that for simple tasks, such as palpation the gain in workspace is not high, but for more complex operations which involve direct contact and interaction with the tissues (grasping, cutting) the gain is very high, offering the surgeon a wider range of action without the need of additional insertion points.

4. CONCLUSIONS

The proposed approach represents a new solution on a worldwide level. The use of multiple bends/curvatures increases the workspace of the instrument, enlarges the surgical field and has a positive impact upon the surgeon comfort and the patient recovery time. Moreover, the modular and simple design generates without additional costs a large variety of solutions which can accommodate various needs during surgery. The preliminary results encouraged the authors to apply for a patent [4]. Future work will try to asses the advantages of the solution in SILS and NOTES.

4. ACKNOWLEDGEMENTS

This paper was supported by the project "Development and support of multidisciplinary postdoctoral programmes in major technical areas of national strategy of Research - Development - Innovation" 4D-POSTDOC, contract no. POSDRU/89/1.5/S/52603, project co-funded by the European Social Fund through Sectoral Operational Programme Human Resources Development 2007-2013.

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PROIECTAREA ŞI ANALIZA UNUI MODUL DE ORIENTARE PENTRU INSTRUMENTE UTILIZATE ÎN PROCEDURILE MINIM INVAZIVE

În lucrare se prezintă o analiză asupra unui modul de orientare a vârfului instrumentului în intervențiile chirurgicale minim invazive. Se vor prezenta o serie de aspecte legate de proiectarea modulară a acestuia scoțând în evidență avantajele acestei abordări. Se va realiza un studiu comparativ între spațiile de lucru a instrumentelor clasice şi a celor echipate cu modulul de orientare subliniind avantajele soluției propuse.

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