

Analysis and Design of a Cable-driven Mechanism for a Spherical Surgery Robot

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Abstract— This paper presents design and analysis of a cable-driven mechanism for a spherical laparoscopy surgical robot manufactured at the Research Center for Science and Technology in Medicine. The design is featured by two types of ‘idler pulleys’, which allow change of cables’ plane of motion in spherical workspace. This robot suffers from back-lash and high friction due to the usage of motor and gear-box in each joint. In order to find a precise and optimal design, the paper studies various designs of cable robots, considering pulleys and cable arrangements, as well as pre-tensioning methods. Final scheme introduces two series of pulleys for each DOF, which transmits power from motors located on base, to the corresponding joints. Each paired pulleys are in relation via two separate cables ending on both pulleys. First and second sets provide 227 and 313 reduction ratio in 3 and 4 stages respectively, resulting 95% and 93% efficiency, assuming 7 year life cycle. The stiffness is assessed by evaluating each paired pulleys’ stiffness and computing the whole series stiffness. Applying the maximum needed torques at the tip, through the entire workspace, we achieved the maximum tip’s displacement, 3.8 mm.

Keywords- Cable-driven mechanism, spherical surgery robot, back-lash, pre-tensioning method, stiffness

I. INTRODUCTION

Minimal invasive surgery (MIS) is substituted the open surgery since 1970. It is preferred due to less infection probability and decreased hospitalization duration. Based on the significance of robotic surgery, a project has been launched, developing a complete master-slave surgical unit. As a part, a 4-DOF robotic arm for laparoscopy is designed by A.Alamdar [1], which includes the roll, pitch, yaw and the insertion (linear) movement (fig.1). The first two DOFs construct the spherical scheme, which define and fix the insertion point of laparoscopic tool to the abdomen. Both degrees are driven by EC-max brushless motors and planetary gear-box, MAXON motor company, which brings back-lash and friction through power transmission.

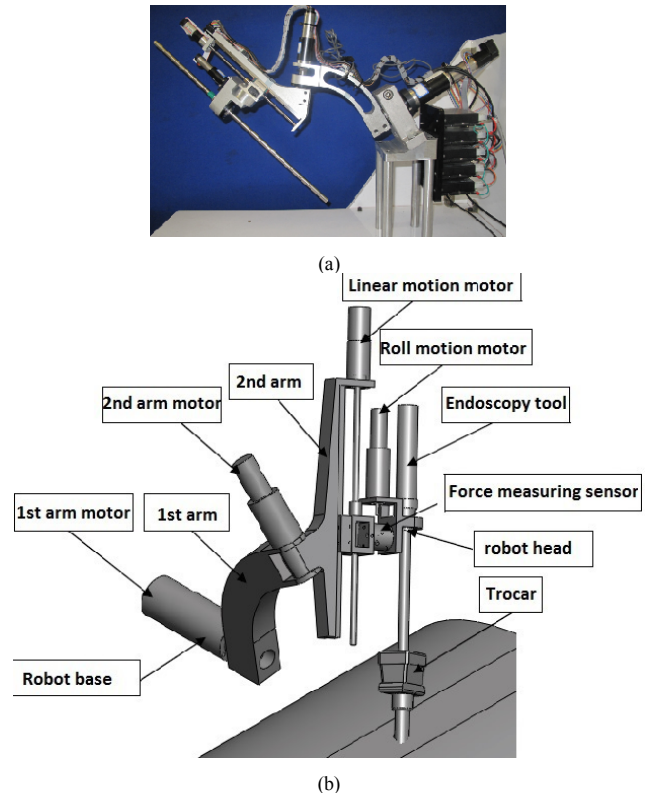


Figure. 1 Spherical surgery robot manufactured at Research Center of Tehran University of Medical Science (a) overall scheme (b) component illustrated [1]

In recent decades, wide experiments have been done in utilizing cable as power transmission system, exposing commercial models, the Whole-Arm-Manipulator (WAM) and Da Vinci robotic arm. Notable aspect of this system could be mentioned as [2]:

- 1) No back-lash
- 2) Small size and light weight

Two recent features are dominant properties for force-control

- 3) High stiffness

- 4) Low friction
- 5) High efficiency
- 6) Affording more flexibility in motor placement

Cable-driven systems have been mainly considered for industrial warehousing, handling and manipulating large and risky workspaces. In [3], cable application is employed for camera positioning in stadium. In [4], the authors devise a crane with cable. Cable robots can be a great substitution for long heavy links, which may be suggested for remote access tasks. This technology also has been mostly appealed in biomedical robotic realm, including lightweight wearable robots [5], rehabilitation purpose [6, 7], and surgical robotic arm requiring haptic feature. Elimination of back-lash and friction, along with providing a force feedback, seems to be a prerequisite for haptic goals.

In this paper, a pulley-cable system is designed in order to upgrade a pre-manufactured surgical robotic arm to the ones suitable for haptic demands. The suggested design has been adapted to the spherical workspace of the aforementioned robot. Cable system is used for the two first degrees of this arm, attaining a plan in which the motors are placed on base and the two arms of manipulator would be driven by cables. Additional analysis on stiffness proves achievement of the desired end-effector precision.

II. CONCEPTUAL DESIGN

A. Pulleys and Cables Arrangement

Recommended cable arrangements are categorized in three classes (Fig.2) [5, 8, 9]:

1. closed-loop
 - 2.1) dual-pulley in each joint
 - 2.2) terminating the cable to the link
 - 2.3) twining the cable around pinion
 - 2.4) have common groove
3. Pulley-time and time-belt.

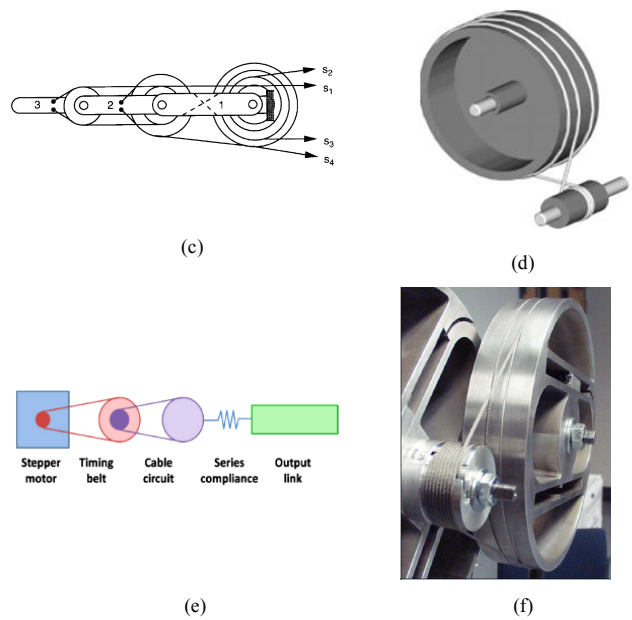
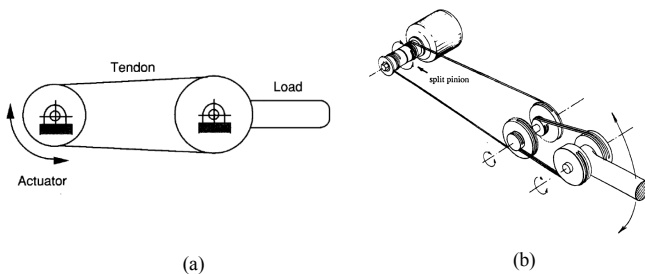


Figure 2. Cable arrangements (a) closed loop (b) dual-pulley (c) termination on link (d) twining around pinion (e) pulley and time belt (f) common groove [5, 8, 9]

Each of (a)-(e) methods are respectively rejected because of possible slippage of cable on pulley, huge space occupation, complexity and high cost, incompatibility with 3D movement and inefficiency in small scales. Thus, style (f) is selected. In this style each pulley is grooved according to necessary turns it would revolve (fig.3). In this manner, first cable turns around the pairing pulley while leaving current pulley and the second cable behaves in opposite.

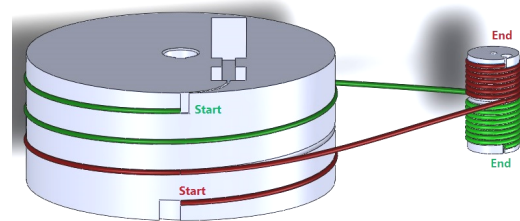


Figure 3. Cable rolling strategy in 'common groove' method

So, the pulley series are driven, each along with 2 cables, terminated on both ends of paired pulleys. 3 and 4 stages are considered for two first joints respectively (Fig.4).

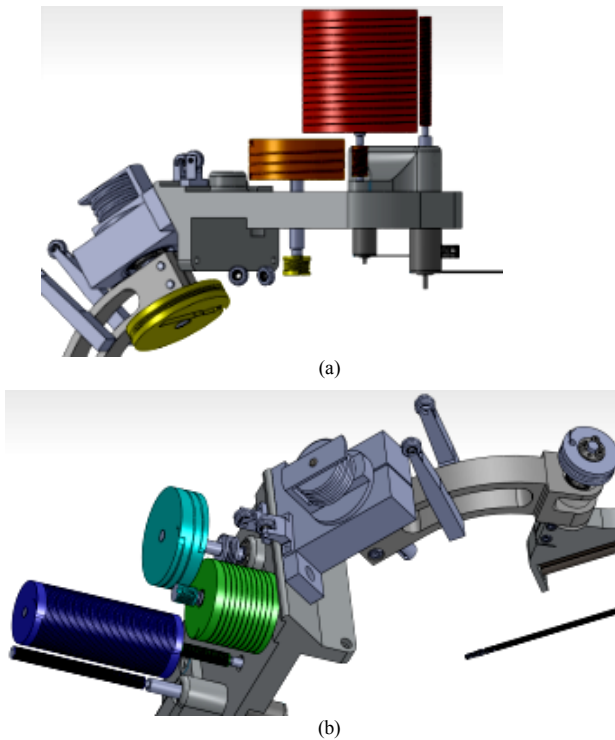


Figure 4. Cable circuit of power transmission (a) 1st joint (b) 2nd joint

B. Idler pulleys design

Two types of idlers are regarded. First class executes a change in the plane of motion of the cable. These idlers should observe these constraints (Fig.5):

- The mid-plane of the idler coincides with the plane which is tangent to the first pulley and passing through the exit point of the cable from the second pulley
- The groove of the idler is tangent to both pulleys' mid-plane.

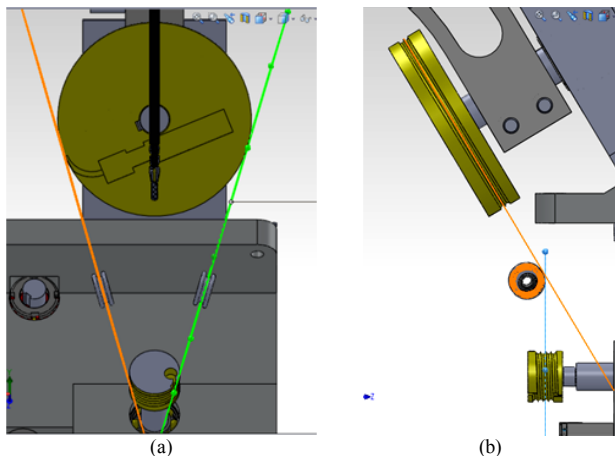


Figure 5. (a) 1st constraint (b) 2nd constraint

Idler class II provides the length compensation of cable of the second set corresponding to the second joint, in their transition to the end, while passing through the first joint and crucially when the 1st joint moves in its workspace. The idea benefits from the fact of unrolling the same cable length from the idler on the previous joint and rolling this exact length on the pulley placed at the current (last) joint. This phenomenon occurs for both forward and backward cables. Two constraints are dictated by these kinds of idlers (Fig.6):

- Being coaxial with the previous joint (1st joint in our design)
- Having the same size as the destination pulley (2nd joint in our design)

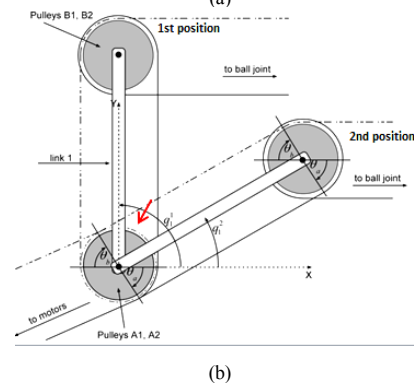
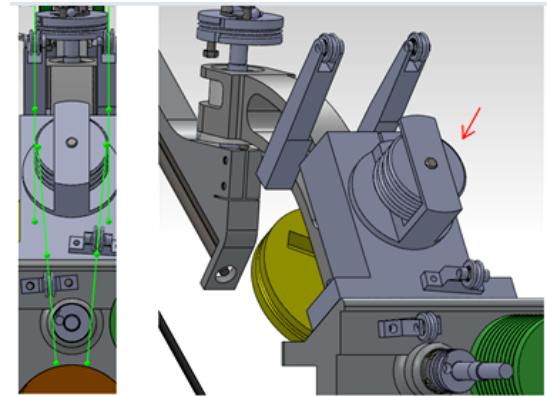


Figure 6. Coaxial idler with the 1st joint passing the cable of 2nd joint's circuit to its destination, preserves its length (a) Current design (b) illustrative sketch [10].

C. Pre-tensioning Methods

In this section, we introduce three methods to pretension the cable. Pre-tensioning enables us to make the whole system stiff (Fig.7). In all three methods, the excess length of cable is removed through a special mechanism installed on the pulley side face. This stretch develops the required pretension in the cable. The needed length to be eliminated could be altered whenever required after installation. The proposed screw in our method also resolves the problem of length and tension change, after installation and long-time running.

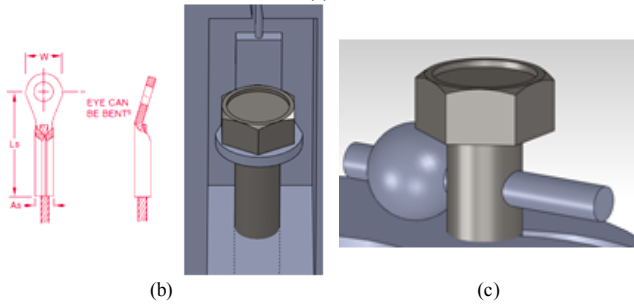
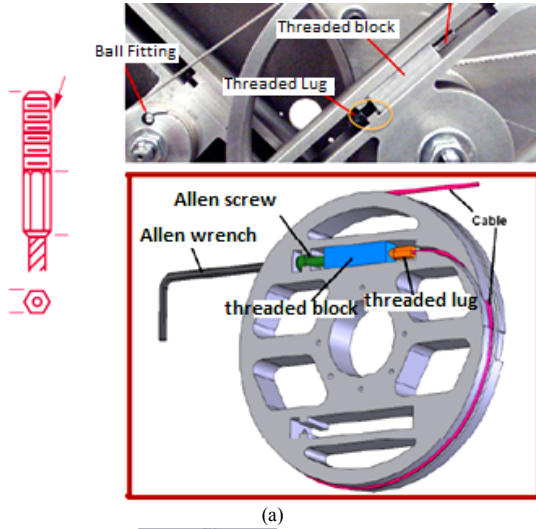


Figure 7. Pre-tensioning methods (a) threaded lug and both end threaded block [5] (b) eyelet lug (c) ball and screw

III. DETAILED DESIGN

Design of components is carried out in three steps: *A.* cable selection, *B.* pulley design, and *C.* idler design. We consider the estimated forces based on the requirement for surgery [1]:

$$\begin{aligned} T_{1z} &= 11.8N.m \\ T_{1r} &= 12.6N.m \\ T_{2r} &= 5.8N.m \\ T_{2z} &= 9.3N.m \end{aligned} \quad (1)$$

T_r and T_z correspond to the radial (perpendicular to axis) and axial torque of each joint.

Unwanted and disturbing loads owing to placement of surgeon hand or other possibilities are estimated as:

$$\begin{aligned} T_{1r-peak} &= 50.4N.m \\ T_{2r-peak} &= 37.2N.m \end{aligned} \quad (2)$$

Safety factor for shafts and bearings is taken 2 and for cable selection, according to manufacturer is 10.

A. Cable Selection

Cable selection has been done through these steps, as the manufacturer, SAVA Inc., recommended [11]:

1) Primary cable selection with minimum breaking strength of 10 times the working load.

2) The pulley's root diameter estimated according to the suggested multiplier n .

$$\frac{D}{d} = n \quad (3)$$

where D is the pulley root diameter and d is the bare cable diameter.

$$n = \begin{cases} 15 & \text{cable 7x49} \\ 25 & \text{cable 7x19} \\ 50 & \text{cable 3x7} \end{cases}$$

Deviation from this ratio decreases the fatigue life and practical breaking strength rather than nominal one (Fig.8).

RATIO "A" = PULLEY DIA. / CABLE DIA.	STRENGTH EFFICIENCY COMPARED TO CATALOG STRENGTH IN %
40	95
30	93
20	91
15	89
10	86
8	83
6	79
4	75
2	65
1	50

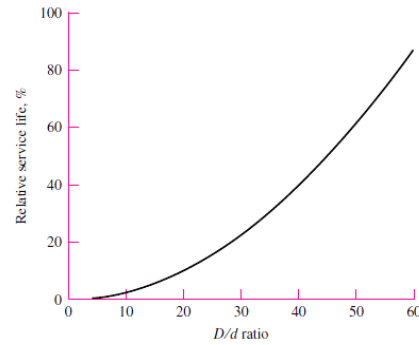


Figure 8. Reduction in breaking strength and fatigue life due to deviation from the recommended diameter ratio [11, 12]

3) Fatigue life (cycles) evaluation: it is calculated according to the Cable-Factor defined by the manufacturer and the following experimental graph (Fig.9).

$$\text{Cable - Factor} = \frac{C.L(lb)}{D(in) * d(in)} \quad (4)$$

Where $C.L$ is the cable load

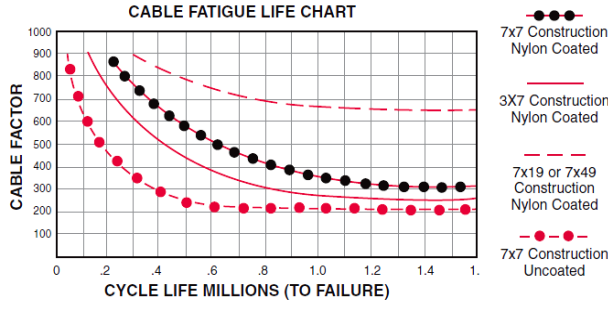


Figure 9. Evaluating fatigue life [11]

B. Stiffness and efficiency

Further examinations of the performance of each paired pulleys are done as follow:

4) Calculation of the torsional stiffness of each paired pulleys:

$$k = 2 \frac{EAR^2_{driven}}{L} \quad (5)$$

In (5), k is the torsional stiffness. E, A are the modulus of elasticity and bare cable cross section. R_{driven} is the driven pulley radius, that is the large pulley; and L is the cable length between two paired pulleys, which is under tension.

Here has been proposed a revision on the strength of a cable; since it constructs a special helical array of cables, rather than a united structure, the mechanical properties of its constructing material cannot be used. Given the only reported property, the stretch characteristics (Fig.10), we conclude:

$$\frac{BS}{EA} = 1.67 * 10^{-2} \quad (6)$$

BS: Breaking Strength

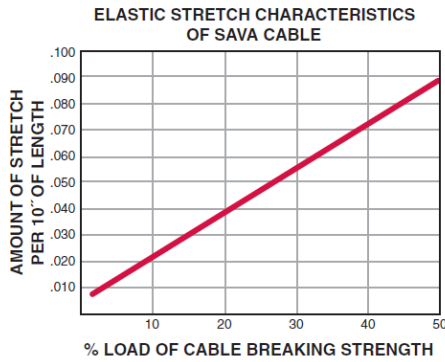


Figure 10. Stretch graph of SAVA cable [11]

5) Efficiency:

In [9], the efficiency of a cable drive system is estimated by thermo-dynamical and energy conservation consideration as:

$$\eta = \left[1 - \frac{T_2 - T_1}{EA} \right]^n \quad (7)$$

T_1 and T_2 are the low and high tension side respectively. n is the number of speed reduction stages.

C. Pulley Design

Pulleys' diameter and cable selection are determined in the last section, at the same time. Two more features of a pulley, helical pitch and groove profile, should be investigated.

The cables experience a traversal or lateral displacement while rolling or unrolling around the pulley. This deviation is implied by assuming pitch relation for each paired pulley [5].

$$\frac{D_1}{D_2} = \frac{P_1}{P_2} \quad (8)$$

Where D_i is the pulley's root diameter and P_i is the pitch.

References [13, 14] have shown that pulleys life cycle could be enhanced by a 5% larger groove diameter.

IV. KINEMATICS AND STIFFNESS

The common procedure to evaluate the precision of robotic manipulator is to define the stiffness matrix under maximum pay-loads.

In our special case of spherical robot with its specific kinematic, a singular compliance matrix arises. This singularity hints the fixation of spherical mechanism, needed for fixation of the insertion point in the patient abdomen. Thus, the inverse of compliance matrix known as stiffness matrix could not be defined. In other words, presuming the structure of robotic arm as rigid parts, we disclaim further analysis for applied force, and just concentrate on tip torques. The compliance matrix can be found in (9) and (10).

$$CT_{end} = \Delta\alpha_{end} \quad (9)$$

$$C = J\chi^{-1}J^T \quad (10)$$

Where J , and C are the Jacobin and the compliance matrix, respectively. T_{end} , containing the maximum tip torques, is $T_{end} = [T_x, T_y, T_z]^T$. Applying T_{end} gives the maximum angular displacement (matrix $\Delta\alpha_{end}$), and:

$$\chi^{-1} = \begin{bmatrix} 1/k_1 & 0 & 0 \\ 0 & 1/k_2 & 0 \\ 0 & 0 & 1/k_3 \end{bmatrix} \quad (11)$$

Regarding cables the same as springs in series, we find the whole pulley series stiffness in (12).

$$\frac{1}{k_{eq}} = \sum \frac{1}{k_i} \quad (12)$$

Where k_i is the stiffness of each paired pulley and k_{eq} is the equivalent one for the whole stiffness of the two joints and the 3rd joint. Rolling of the tool is assumed to be rigid.

Consequently, maximum tip torques could be applied through the entire workspace of the robotic arm. $\Delta\alpha_{end}$ determines the resultant displacement.

V. RESULTS

Table .I summarizes the final results. (D_l) the diameter of the large pulley, (D_s) the small pulley diameter, and the cable numbers are mentioned.

TABLE I. DESIGNED PULLEYS AND CABLES

1 st (yellow)	2 nd stage(orange)		3 rd (red)	1 st joint
$D_s = 26$ $D_l = 100$ #2081SN3	$D_s = 15$ $D_l = 90$ # 2047SN		$D_s = 11$ $D_l = 108$ # 2019SN	
1 st (gray)	2 nd (turquoise)	3 rd (green)	4 th (blue)	2 nd joint
$D_s = 27$ $D_l = 50$ #2081SN3	$D_s = 16$ $D_l = 85$ #2047SN	$D_s = 11$ $D_l = 70$ #2019SN	$D_s = 11$ $D_l = 55$ #2009SN	

Stiffness analysis for this design set shows maximum displacement 3.8 mm.

VI. CONCLUSION

All steps needed for the design of a cable-driven actuation system of a spherical robot were presented. The design was shown to be based on a series of pulleys for each degrees of freedom of the robot. The special technique for fixation of the cables on each side of a pulley, and the pre-tensioning strategies, brings a more accurate motion without slippage or loosening of either forward or backward cable. It also outweighs the schemes with 2N forward/reverse cables – in nDOF robot —, having less complexity. This idea enables locating motors on the base; while the novel idlers introduced here make the change of cables' plane of motion possible in 3D workspace.

Further analysis on the end-effector precision and stiffness was carried out by considering stretch properties of the Sava Inc. cables. Results proved the capability of the design to afford the desired precision necessary for surgical applications.

In this paper, the motors were already selected and the cable drive was designed to suit them. In order to achieve an optimum design, the entire power system as well as the whole robot; including the motors, links, and cable series; need to be optimized; which is considered for a future work. In addition, the linear relation between the cable force and its stretch, known as Hook's law, allows an effective force control for future studies.

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