New Control Mechanism for PoLaRS SATA Multi-DOF Instruments- Design and Validation

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***Abstract*— The FDA approval of the Senhance Surgical System by Transenterix has given a boost to the field of robotic surgery that was dominated by Surgical intuitive with the Da Vinci Surgical systems. The use of these systems is limited to High Income Countries (HIC) and a few Low and Middle Income Countries (LMIC) due to their cost and lack of trained surgeons. This makes it difficult for those systems to be adopted in LMIC, even though the benefits of robotic surgery are magnified in these countries.**

The PoLaRS has the goal of being cost effective, light weight, easy to clean, compact and portable. The Shaft Actuated Tip Articulation (SATA) instrument was born out of a new bare minimum design philosophy with a focus on component interaction and uses the rotation and translation of its cylindrical shaft tubes to move the gripper in pitch, yaw and open/close.

A newly developed control box and Z translation mechanism (ZTM) is used to control these extra DOF's for tip steering and instrument insertion or removal. The control box is linked to a special coupling that allows the control box to remain sterile while the instruments are used during surgery. The box uses timing belts and pulleys to drive the coupling pieces that actuate the SATA instrument shaft tubes and therefore rotate, pitch and yaw the gripper. Within the control box, the opening/closing of the gripper (i.e. translation of the middle tube) is actuated by a leadscrew mechanism in the control box, which moves the middle control box coupling piece linearly. Additionally, a mechanism to detach the coupling pieces in case of emergency is also implemented in the control box. For instrument insertion and removal, the ZTM uses a leadscrew mechanism to drive the control box over its slide, which moves the SATA instrument towards and away from the surgical site.

The developed functional prototype shows that most of the set requirements were met. However, there are limitations on the torques obtained and materials used in the prototype. Improvements can be made in design of the timing belt and tolerances of the parts to build a better prototype.

***Keywords*— PoLaRS, robotic surgery, tele-operation**

I. Introduction

The recent FDA Approval of Senhance Surgical Robotic System by TransEnterix in October 2017, provided further backing to the field of robotic surgery, since 2000 by Da Vinci Robotic Surgical Systems by Intuitive Surgical [1].
In this type of robotic surgery, the surgeon controls the slave device through the master console to perform the surgery. The slave device consists of the robotic arms and the surgical instruments, which can be manipulated by the surgeon to perform the surgery [2] [3].

There are several advantages of robotic laparoscopy over conventional handheld laparoscopy [4] [5] [6]:

- Ergonomic position for the surgeon
- Increase in dexterity
- Higher precision and accuracy of movement
- Tremor filtration
- Data for training surgeons etc.

There are also disadvantages with robotic laparoscopy [4] [7]:

- High costs
- Large sizes
- Lack of compatible instruments
- Lack of haptic feedback
- Risks due to surgeon being away from the operating table etc.

In Low and Middle Income countries (LMIC) the use of surgical robotic systems is gaining momentum. There were around 200 surgeries performed in India from 2006 to 2012 using surgical robots. There were 8 Da Vinci Robots in India in the year 2012, with plans to increase it further by 200 more by 2020 [10] [11]. The high cost of these systems and lack of trained surgeons are major setbacks [8] [9], which need to be reduced.

A. *Technology Background*

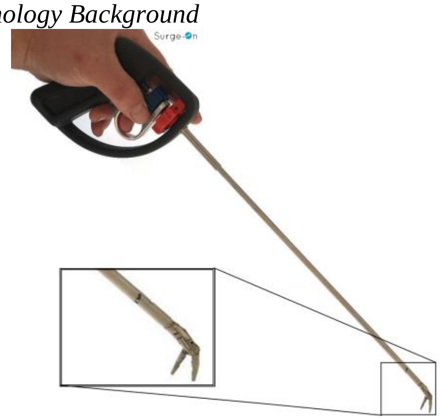

Fig. 1. 5mm Steerable Grasper with the SATA mechanism

The Shaft-Actuated Tip Articulation (SATA) Instrument by Surge-On Medical B.V. is to be used in the PoLaRS. The instrument moves its gripper in pitch and yaw by rotating its cylinders. The gripper at the instrument tip is opened and closed by translating the middle cylinder of the SATA Instrument. The

steerable grasper and the steerable punch gripper use the SATA mechanism (Fig. 1) [12].
The SATA Instrument movement range is ±60 degrees for pitch and yaw. It is rotated by hand and hence a maximum of ±90 degrees rotation is sufficient. While for the gripper, the opening and closing is 40 degrees. All these movements correspond to the rotations of the SATA Instrument shafts and the linear motion of the middle shaft. The shafts need to rotate ±90 degrees to achieve the movement range of ±60 degrees. While the middle CBC piece has to move linearly 4mm to achieve the movement range of 40 degrees.

Fig. 2. CBC and IC pieces for coupling the control box and the SATA instrument

The coupling mechanism provides a connection between the SATA Instrument and the mechanisms inside the control box. It consists of 2 parts, the control box coupling (CBC) piece and the instrument coupling (IC) piece (Fig. 2). The coupling pieces connect to each other on one side and connect to the SATA instrument and the control box on the other sides. It allows easy coupling and decoupling of the SATA instrument from the control box [13].

A. Requirements

The requirements are written separately for the ZTM (Z translation mechanism) and the control box. Within the control box and the ZTM the requirements are further split into Design, Performance and Safety requirements.

Design Requirements control box
1) Attachment and removal of SATA instrument.
2) Smooth movement of the SATA instrument.
3) No backlash [19].
4) Weight below 1kg.
5) Compact size under 84mm*290mm*150mm.
6) Attachment for drape holder.

Performance Requirements control box
1) Translational speed of middle CBC of 4mm/s.
2) Linear movement of middle CBC of 4mm.
3) Speed of gripper in pitch of at least 0.5 rad/s [2] [3].
4) Speed of gripper in yaw of at least 0.5 rad/s [2] [3].
5) Speed of gripper in roll between 3 rad/s to 4 rad/s [2] [3].
3) Rotational resolution of at least 0.5 deg. [3].
4) SATA instrument pitch between ±60 deg. to ±90 deg. [3].
5) SATA instrument yaw between ±60 deg. to ±90 deg. [3].
6) SATA instrument roll between ±75 deg. to ±90 deg. [2] [21].
7) SATA instrument gripper load of at least 10N [2] [3].
8) CBC torques above 80Nmm.

Safety Requirements control box
1) Backdrivable [20].
2) Sterilizable [22].

Design Requirements ZTM
1) Easy attachment and removal of control box.
2) Smooth movement of ZTM.
3) No backlash [19].
4) Weight below 2kg.
5) Compact size under 200mm*200mm*400mm.
6) No interference with drape.

Performance Requirements ZTM
1) Translational speed between 60mm/s to 200mm/s [3] [17].
2) Linear movement range 200-350mm [16] [17].
3) Linear resolution of at least 0.1mm [3].
4) Pull-push force of at least 26N [18].

Safety Requirements ZTM
1) Backdrivable [20].

II. Materials and Methods

The design of the system involved iterative design steps. A general process of design-development was used to come up with the final design.
The design process involved the following steps:

1) Define the goal
2) Gather information about the goal
3) Sub-divide the goal
4) Brainstorm multiple solutions for each sub-goal
5) Select solutions and define further for each sub-goal
6) Combine the selected solutions to obtain the main goal
7) Test the feasibility of the solution.
8) Manufacture the solution
9) Test the solution
10) Iterate on the solution by comparing with the goal
11) Finalized solution

Pugh Matrix Analysis (PMA) was used to obtain better solutions from a set of solutions obtained from brainstorming sessions. After the design was completed, a prototype was made and tested. Further improvements in the design were implemented after the phase 1 testing, after which phase 2 testing was carried out on the improved prototype.

A. Complete Assembly of the PoLaRS Slave Arm

The control box and the ZTM mount on the PoLaRS slave arm (Fig. 3) which is connected to a base. Each base has 2 PoLaRS slave arms on it. The arm tilts in the forward-backward and left-right directions, which moves the ZTM and control box assembly with it.
The PoLaRS slave arm has 7 DOF in total, which includes the 4 DOF from the control box, 1 DOF from the ZTM and 2 DOF from the slave arm.

Fig. 3. Control box and ZTM attached to the PoLaRS slave arm

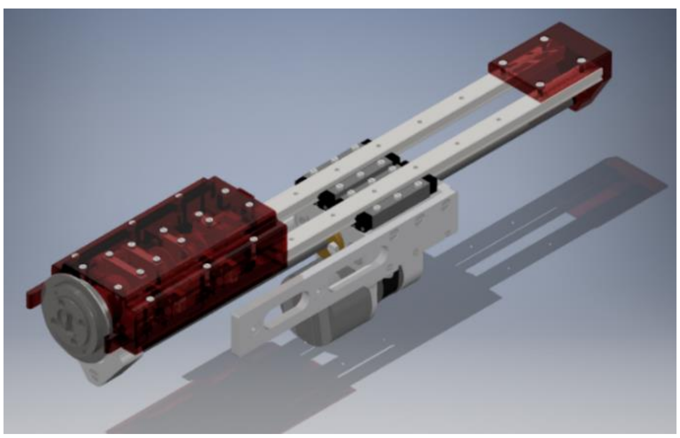

Fig. 4. ZTM with the control box attached

B. ZTM

The control box is attached to the ZTM by means of 4 nuts and socket screws. This moves the control box along with the slide rails when the slides move linearly. This moves the instrument attached to the control box towards and away from the surgical site (Fig. 4).

The slide rails are moved by means of a leadscrew passing through the threaded center of the timing pulley. The leadscrew is driven by means of a timing pulley and timing belt system. The driven pulley is rotated by a brushless dc motor, which rotates the driven pulley connected by a timing belt. The rotation of the driven pulley is transferred to the leadscrew through threads at the center of the driving pulley.

The ZTM (Fig. 5) (Fig. 6) has a single motor (12), which rotates a pulley (10) by using a belt (9).

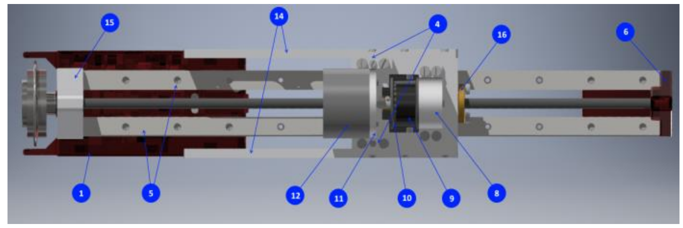

Fig. 5. ZTM numbered back view

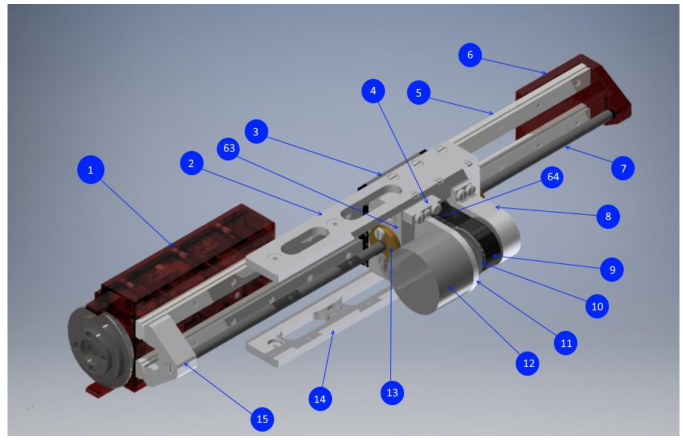

Fig. 6. ZTM numbered orthogonal view

Another pulley (64) closer to the leadscrew (7) is also connected to the other end of the belt (9).The pulley (64) has trapezoidal threads internally through its center. These threads mate with the threads of the leadscrew (7). When the pulleys (64, 10) rotate, the leadscrew (7) moves translationally along its axis through the center of the pulley (64). The pulley is fixed in a small gap by using 2 end parts (13, 16). These ensure that the pulley (64) does not travel with the leadscrew and only rotates. There are 2 slides (3, 5) in the system to guide the mechanism box (1). The slides are attached inverted with the travelling part (3) fixed on the main body (63) and the slides (5) allowed to move translationally only. The leadscrew pulls/pushes the end parts (6, 15), which moves the control box on the slides with it. The slides are kept in position by using a 3-D printed end (6) and the control box. This ensures that the slides are not misaligned and are parallel to each other. The motor is attached to an aluminum plate (11) by using the holes provided in the motor. The aluminum plate (11) is fixed on the main body (63) by means of 2 tiny holders (4). The shaft of the motor is extended to hold the pulley (10) and to support the other end in a bearing on a motor shaft support part (8). This ensures that the motor shaft does not bend due to the bending forces arising from the belt.

The ZTM support parts are made from 7075 aluminum, these are watercut and later machined further to obtain the final part. The guides for the leadscrew is made of bronze, the leadscrew is made of steel and the slides are made of carbon steel. The plastic parts are 3-D printed by using R05 material. The timing pulleys are made of steel. The slides, leadscrew timing pulley and belt are off-shelf products.

C. Control Box

The control box is used to control the pitch, yaw, rotation of the SATA instrument and opening/closing of the gripper (Fig. 7). The mechanism inside the control box move the CBC piece, which in turn move the IC piece and the SATA instrument shafts. The range of the rotations of the CBC pieces are ±90 degrees. The middle CBC piece has to move linearly apart from the rotation. The linear distance travelled by the middle CBC piece is 4mm. In order to detach the IC from CBC, the middle CBC piece is pulled back 2.5mm beyond its working range.

The control box also has an additional mechanism for manual disconnection and removal of the SATA instrument in case of emergencies. The outer CBC piece is pushed back towards the control box. After the outer CBC piece moves some distance, the middle CBC piece is engaged, which moves back the CBC and exposes the inner CBC piece, which can then be disengaged from the inner IC piece. The CBC and IC can then be detached.

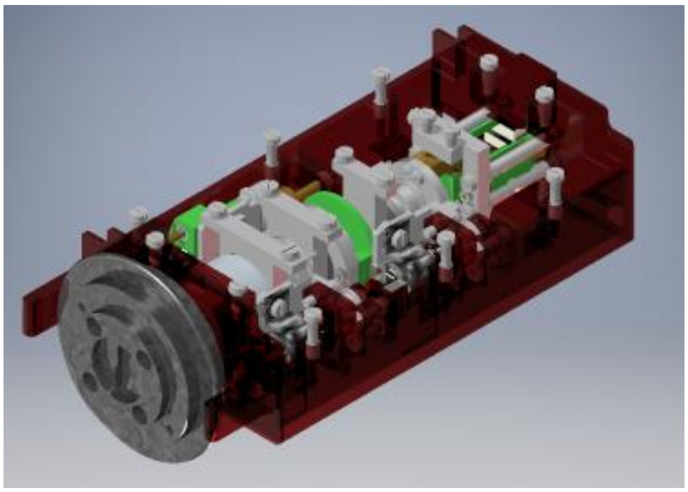

Fig. 7. Control Box without top cover

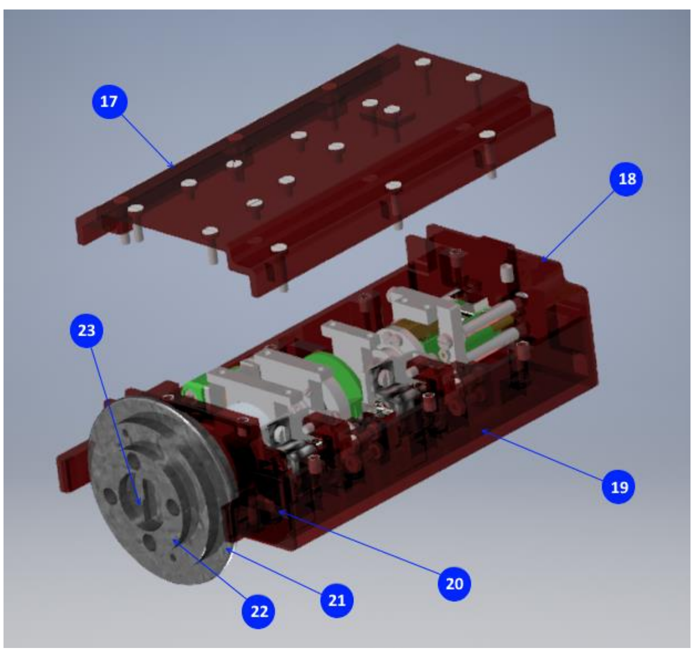

Fig. 8. Control box numbered orthogonal view

The control box (Fig. 8) (Fig. 9) is made of 4 cover parts (17, 18, 19, 20), which forms the box in which the other components are fitted. There are 4 motors (59, 33, 41, 49) in the control box, 3 motors (33, 49, 41) are connected to the pulleys (51, 31, 39) which have a cable running through it and passing on to other pulleys (32, 37, 40) attached to one of the CBC pieces (inner, middle or outer).

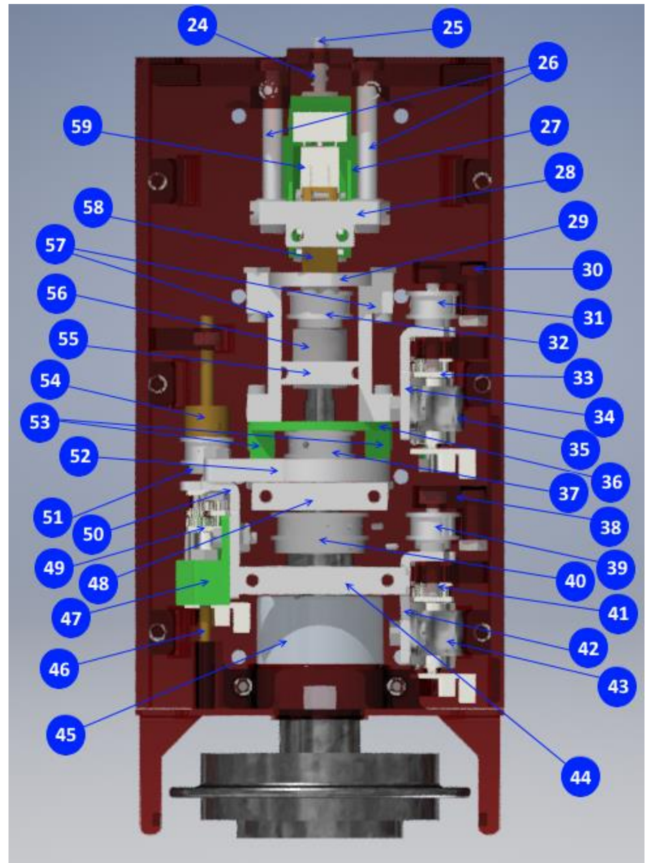

Fig. 9. Control box front view

The motors (33, 41) are fixed by means of a motor bracket (42, 34), plastic support (35, 43) and bushing parts (30, 38). The other motor (49) is held by the motor bracket (50), plastic support (47) and longer bushing part (54).

When the pulleys rotate due to the motors, it pulls on one side of the cable, which causes the pulleys fixed to the CBC piece to rotate, which in turn rotates the CBC pieces (21, 22, 23). When the direction of the motor is reversed, the pull is on the other side of the cable and the CBC pieces rotate in the other direction. The CBC pieces are held in place by means of 3 holders (44, 38, 55). There is a bushing (45) between the box part (20) and the outer CBC coupling to allow smooth rotation. The inner CBC piece is prevented from falling out of the control box by means of a shaft collar (56), which touches the holder (55).

The other motor is connected to a tiny threaded leadscrew (61). This leadscrew connects to the thread inside a nut part (29). This arrangement is similar to a screw nut mechanism, when the screw is rotated the nut will move forward or backward. The nut part is held in place by means of 2 rectangular supports (57) Thus when the leadscrew is rotated the entire mechanism for the translation, also moves translationally. The mechanism is guided by means of 2 rods (46), which move in holes in the box part (20) and the guide bar (58) which mates with the 2 L-blocks (28). The middle pulley (37) also moves along with the middle CBC piece (22). This movement of the middle pulley (37) is obtained by sandwiching the middle pulley (37) between

the support arm (52) and a circular disk (36). There are 2 spacers (53) which prevent the crushing of the middle pulley (37).
Another important mechanism inside the control box is for the detachment of the SATA Instrument in case of emergency i.e. emergency decoupling to remove the IC and SATA instrument from the CBC. The requirement was that the middle CBC piece (22) should be able to be pushed back by at least 2.5mm, when the middle CBC piece is completely pulled in by the motor (59) in the motor box (27) and 6.5mm, when the middle CBC piece is completely pushed out by the motor (59). The motor (59) is guided by rods (26) and guides (60), which ensure the motor only translates.

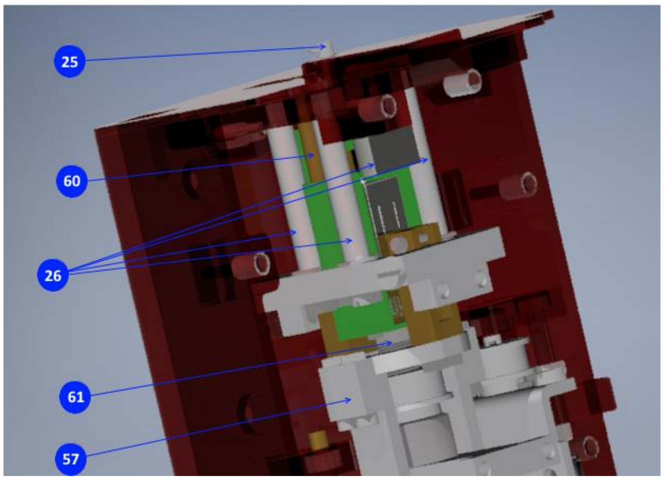

Fig. 10. Control box angled view, showing the emergency (middle CBC piece) pushback mechanism for decoupling the coupling pieces

For this mechanism, a spring (24) and a spring support (25) was used to provide constant pressure to the motor connected to the tiny leadscrew (61) so that the screw nut mechanism can have contact at all times. This constant spring pressure is held by 2 L-blocks (28). In case of emergencies the middle CBC piece along with the motor and the entire middle CBC translation mechanism will be pushed back by pushing on the outer CBC piece (21), which compresses the spring (Fig.. 10) and once released the spring will set back the middle CBC translation mechanism to its normal position.
The control box is made of aluminum, steel, bronze and plastic parts. The support structures that do not move against any other component are made of aluminum, this includes the 2 L-blocks, (28), rectangular supports (57), motor brackets (42, 50, 34) etc. The parts that slide against each other are made of bronze and steel, these include guides (60), spring support (25), leadscrew (61) etc. The control box itself is made by 3-D printing R05 material. The timing belt is made by 3-D printing polyflex material. There are several techniques used for the manufacture of these parts, which include watercutting, lasercutting, 3-D printing, milling, turning etc.

D. Calculations for the Design

Calculations for the motor torques, speeds, belt size and springs are performed to obtain the needed values to procure components online.
The middle CBC piece translation, the values obtained were a torque of at least 16Nmm and a speed of at least 4800rpm for the motor to lift a load of 3kg, using the equation 1[14] and equation 2 respectively.

$$T \geq r * \left(\frac{\mu + tan\gamma}{1 - \mu * tan\gamma}\right) * w \qquad (1)$$

$$N = rps * p \qquad (2)$$

Where,
r is the radius of the leadscrew.
μ is the coefficient of friction.
γ is the lead angle
rps is revolutions per second of the leadscrew

The ZTM, the values obtained were a torque of at least 41.13 Nmm and a speed of at least 2400rpm, to be able to lift a load of 5kg, using equation 1[14] and equation 2 respectively.

The belt length needed was found to be 210mm with the center distance of 50mm, using equation 3 [15]

$$L = \frac{\pi}{2} * (D + d) + 2 * C + \frac{(D-d)^2}{4*C} \qquad (3)$$

Where,
L is the length of the belt .
D is the radius of the driven timing pulley.
d is the radius of the driven timing pulley.
C is the center distance between the two timing pulleys.

The spring constant obtained is 2.5N/mm, when the spring push back force is assumed to be 30N, using equation 4.

$$F = k * \Delta x \qquad (4)$$

Where,
Δx is the change in the spring length .
F is the spring force.
k is the spring constant.

E. Tests

The tests were carried out at MISIT lab, TU Delft. The equipment used to perform the measurements were; Two pull-push gauges- *Model ANF-50 (capacity 50N, min unit-0.5N (Fig.13))* for the control box and Model ANF-*100 (capacity 100N, min 1N (Fig. 12)) for ZTM.* Power supply unit *(digimess® DCPOWERSUPPLY HY3003 0-30V, 0-3A (Fig. 14))* Markers- *(3-D printed from PLA to measure torques, range of motion and speed of CBC (Fig. 11)).*Video capturing device, vernier caliper, clamps and holders.

Each of the tests had 3 measurements taken, the values of these measurements were then averaged to obtain the final value.

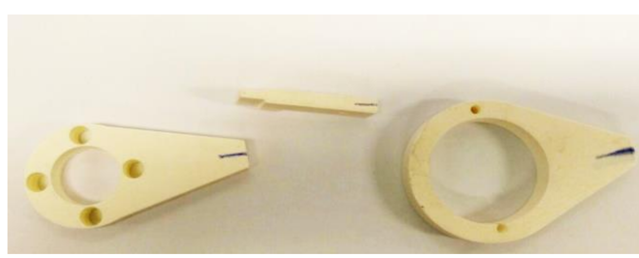

Fig. 11. Markets for testing torques, range of motion and speed of CBC pieces

Fig. 12. Pull/push gauge 50N used for torque and force measurement of control box

Fig. 13. Pull/push gauge 100N used for the force measurement of ZTM

Fig. 14. Power supply digimess® DCPOWERSUPPLY HY3003 0-30V, 0-3A used to supply power to the control box

The tests for the control box measure:

1) The range of motion of CBC

The control box was held vertically and the marker for each of the CBC piece was placed on it, one at a time (Fig. 15). A video camera was placed directly above it and the motion is recorded. The start and end points were captured and then overlaid in paint.net software to obtain a single image with the start and end positions of the markers. The image was then opened in ImageJ to obtain the angle between the start and end position of the markers.

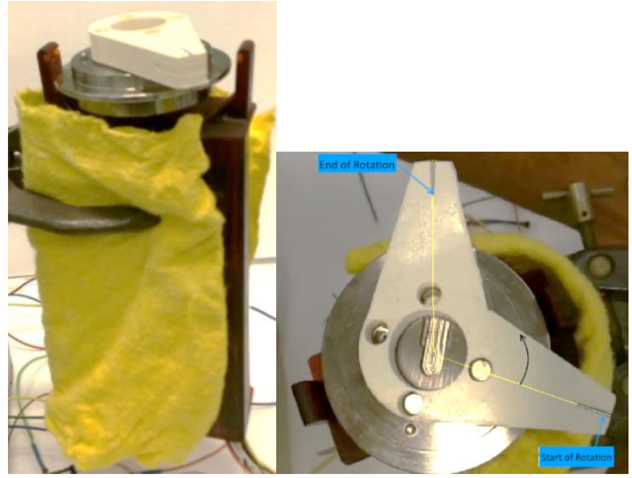

Fig. 15. Right-Control box clamped vertical with the marker for middle CBC placed, Left-Angle between start and end points measured in ImageJ software

2) The speed of pitch, yaw and rotation of CBC

The setup was the same as in test 1(Fig. 15), but the video camera recorded the motion and was played back though VLC media played with the Jump to time (Previous frame) v2.1 plugin, which enables the video to be played/stopped at milliseconds. This was then used to obtain the time one complete rotation takes, to obtain the speed.

3) The range of manual pushback for middle CBC

The control box was held horizontally using a clamp (Fig. 16). The middle CBC piece was pushed back by hand and the distance it has moved was measured using vernier caliper. The measurement was taken at 2 instances, when the middle CBC piece was pushed out completely by the motor and when the middle CBC piece was pulled in completely.

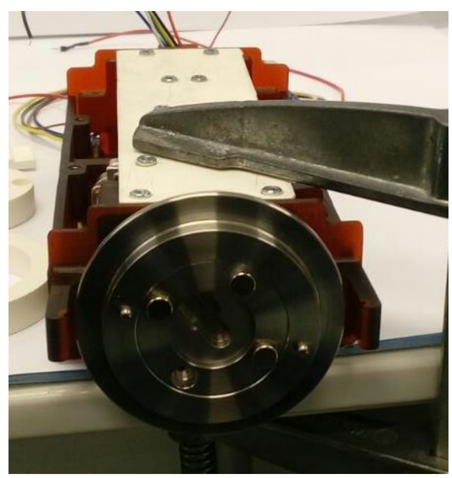

Fig. 16. Horizontal clamped control box for test setup of test 3, test 4 and test 5

4) The linear range and speed of middle CBC

The setup was the same as in test 3 (Fig. 16), with the addition of a video camera mounted to capture the top view of the control box. The motor for the leadscrew was activated and the middle CBC was moved linearly. This movement was measured using vernier caliper and the movement was recorded by the video camera.

The recorded video was played back on VLC media player with the Jump to time (Previous frame) v2.1 plugin and the speed was determined by observing the time it takes to cover the range of motion.

5) The push/pull forces of middle CBC

The setup was same as in test 3 (Fig. 16), the ANF-50 gauge was used to measure the force that the middle CBC piece pushes/pulls with.

6) The torques of CBC

The control box was held vertically in a clamp with the marker in place. On another clamp the ANF-50 gauge was attached (Fig. 17).When the CBC pieces are rotated they will rotate the marker with it and the marker will push on the gauge. Knowing the force measured by the gauge and the distance at which it was measured we can obtain the torque using,

$$T = F * distance \qquad (5)$$

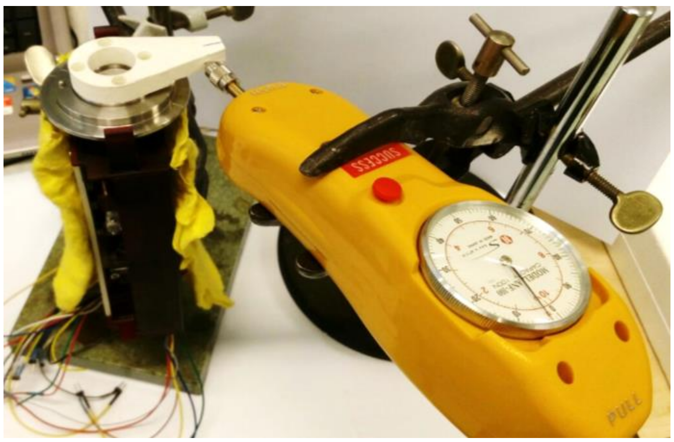

Fig. 17. Vertically clamped control box and the ANF-50 pull/push gauge for test setup of test 6

The tests for the ZTM measure:

1) The range and speed of ZTM

The ZTM was mounted horizontally using clamps, with a video camera capturing the top view (Fig. 18). The start point of the movement was marked on the slides and when the slides move to the other end, the point was marked. The distance between these points was measured to obtain the range. The video camera recording was played back in VLC using the Jump to time (Previous frame) v2.1 plugin and the time taken to complete this range was measured, to obtain the speed.

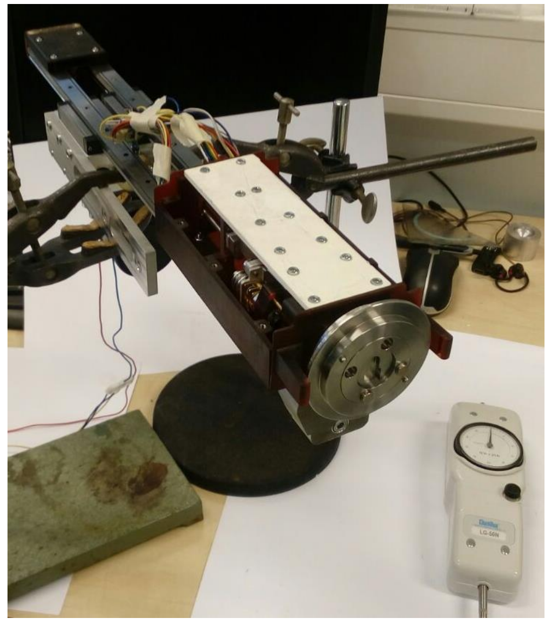

Fig. 18. Horizontal fixation of the ZTM for test setup of test 1

2) The pull/push forces of ZTM

The ZTM was fixed horizontally, but on its side and the ANF-100 pull/push gauge was fixed using another clamp touching the end holder (Fig. 19). The motor for the leadscrew was turned on and the slide moves towards and away from the pull/push gauge providing a force measurement.

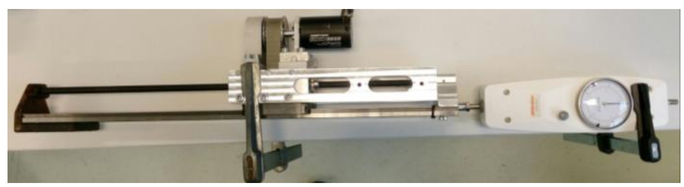

Fig. 19. Side horizontal fixation of the ZTM for test setup of test 2

3) The critical angle speed of ZTM

The ZTM was held by hand vertically and the video camera captures the video horizontally. The time taken for the ZTM to cover the range was measured from the video played back on VLC media player using the Jump to time (Previous time) v2.1 plugin.

There are 2 phases of tests carried out with the tests mentioned earlier. In the first phase of the tests the cable pulley system was used in the control box and a dc motor in the ZTM. After correcting the problems arising in phase 1 tests; phase 2 tests were carried out. In phase 2 tests, the timing belt and pulley system was used in the control box and a new brushless dc motor was used in the ZTM.

III. Results

The results reflect the fully functional prototype with selected motors, belts and springs and the results of the tests.

A. Prototype

The ZTM (Fig. 20) and control box (Fig. 21) were prototyped. The weight of completed prototype was 3217g with the control box 435g (without the CBC) and ZTM 2782g.
The dc motors used in the prototype were 155rpm (torque 0.0686Nm), 52 rpm (torque 0.196Nm) x2 and 41 rpm (torque 0.245Nm) motors, which were used for the middle CBC linear movement, inner, outer CBC and middle CBC rotations respectively.

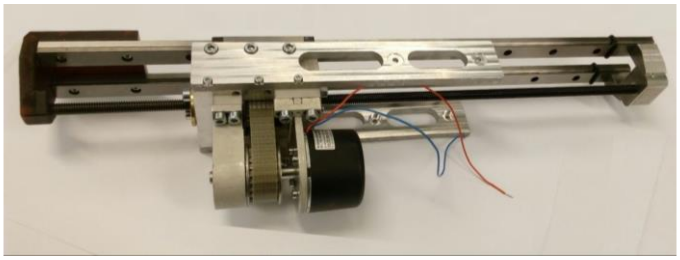

Fig. 20. Prototype of ZTM

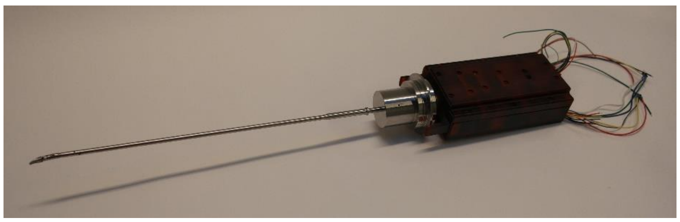

Fig. 21. Prototype of control box with coupling pieces and SATA instrument attached

The speeds and torques provided by the motors to the timing pulleys were calculated theoretically as 27.36rpm (torque 0.372Nm), 29.2rpm (torque 0.343Nm) and 40rpm (torque 0.254Nm) for the outer, middle and inner CBC pieces respectively.
The middle CBC linear movement had a calculated speed of 1.29mm/s with a load capacity of 13kg. The ZTM dc motor (speed 4550rpm, torque 0.03Nm) had a calculated speed of 113.5mm/s and a load capacity of 3.6kg. However, in practice the ZTM motor was not able to move the control box. Therefore was replaced by a brushless dc motor (3800kv), which gave a speed of around 300mm/s and a load capacity of around 10kg in practice.
The belt sizes needed was 210mm, however this belt size was unavailable and therefore a belt size of 225mm was chosen and the center distance was increased by 7.5mm; from 50mm to 57.5mm.The forces generated in the belt due to the torques of the motors were calculated as 39.2N for 52 rpm (torque 0.196Nm) motor and 49N for 41 rpm (torque 0.245Nm). The force due to pretension in the belt wwas 0.092N.
The spring for the emergency detachment of the coupling pieces selected had a spring constant k=2.91N/mm, free length of 18mm,outer diameter of 4.12mm and a coil thickness of 0.6mm.

B. Tests Results

We managed to execute all tests without losing the structural integrity of the metal components and electric motors. We found however that the plastic components were deforming during the experiments and we build replacement ribs for further testing.

Control Box

		Phase 1	Phase 2
Test 1	Inner CBC	480.6 deg.	∞ deg.
	Middle CBC	467 deg.	∞ deg.
	Outer CBC	323.6 deg.	∞ deg.
Test 2	Inner CBC	2.8 rad/s	3.1 rad/s
	Middle CBC	2.04 rad/s	3.3 rad/s
	Outer CBC	1.88 rad/s	2.3 rad/s
Test 3	Pulled in	2.5mm	2.51mm
	Pushed out	6.15mm	4.77mm
Test 4	Range	3.6mm	3.71mm
	Speed	1.55mm/s	0.99mm/s
Test 5	Pull force	5.25N	7.75N
	Push force	4.75N	11.55N
Test 6	Inner CBC	0.0625Nm	0.06Nm
	Middle CBC	0.1Nm	0.04Nm
	Outer CBC	0.058Nm	0.06Nm

Table 1. Results of control box tests

ZTM

		Phase 1	Phase 2
Test 1	Range	403mm	403mm
	Speed	-	302.6mm/s
Test 2	Pull force	-	96N
	Push force	-	98N
Test 3	Speed	-	283.75mm/s

Table 2. Results of ZTM tests

IV. DISCUSSION

The mechanisms for controlling the SATA instrument were successfully prototyped. There are 4-DOF controlled by the control box and 1-DOF controlled by the ZTM. There is a new method of manufacturing timing belt and pulleys tried out as well. The prototype was able to show the needed movements of the CBC pieces, the attachment and detachment of the IC piece and movement of the control box.
In the testing phase, the successful tests include the range of motion and speed of CBC pieces, manual pushback for decoupling CBC and IC pieces, range and speed of ZTM, pull/push forces of ZTM and the ZTM speed for critical angle. These tests had measurements above the needed values.
In test 1 of the control box; the range of motion of the CBC pieces, it was observed that they can rotate continuously in both clockwise and counter-clockwise directions. A rotation beyond 180 degrees can damage the SATA instrument, hence it is necessary that the rotation can be stopped under 180 degrees through software. The motors that drive the CBC pieces have encoders fitted on them. These encoders are incremental and can count the number of steps, indicating the position of the shaft. However, the zero position is not defined in incremental encoders. Installing a hall sensor on the timing pulley with a magnet to indicate the zero position is a possible way of defining the zero point. Knowing the zero point we can decide

the number of steps the encoder has to take so that the range of motion does not exceed 180 degrees.

In test 3 of the control box; it is seen that in phase 1 and phase 2, when the middle CBC is pushed out completely. The manual pushback results in 6.15mm and 4.77mm respectively, which are lesser than the needed value of 6.5mm. However, upon testing the control box CBC and IC detachment, it was found to be working even with 4.77mm pushback.

In test 4 of the control box, it was seen that the speeds are 1.55mm/s and 0.99mm/s, which is less than the needed speed of 4mm/s to open/close the gripper. This is due to the 155rpm dc motor used. Another dc motor of the same type but with a different gearbox having a speed of 530rpm was tried, but the torque of this motor was not sufficient to move the middle CBC piece. It can be possible with higher tolerance manufacture of the components in the control box that the middle CBC piece is moved with the 530rpm dc motor. Otherwise, a new motor will need to be selected that can provide a higher speed and torque.

In test 6 of the control box; during the phase 1 testing it was observed that the cable pulley system had the problem of slipping with use as it became loose. The torques obtained were lesser than the needed value except the middle CBC piece, which had sufficient torque above 0.08Nm. In phase 2 testing, the cable pulley system was replaced by a timing pulley and belt system. The torques obtained remained almost the same, except the middle CBC piece, which decreased to 0.04Nm. The reason for these torque values is due to the stretching of the timing belt. The belt is made of flexible and stretchable 3-D printing material polyflex. This causes the belt teeth to stretch and slip over the timing pulley teeth, when the force in the belt is too high. This prevents a higher torque to be transmitted to the CBC pieces.

Since the timing belts and pulleys needed were of small size, it was difficult to procure them online. Hence they were manufactured in the MISIT lab, TU Delft. The timing belts were 3-D printed using polyflex from polymaker. The timing pulleys were made from 3 parts, the timing pulley base, the teeth and the cover. The teeth were lasercut from aluminum, the base and cover were machined on the lathe. The teeth were glued on the base and the cover was placed over it. The tooth profiles were obtained from online drawings and then were modified to fit the precision of the 3-D printer for the belt and lasercutter for the timing pulley teeth. Another method of manufacturing timing belts would be by creating a mold and then pouring the material with reinforcing cables in the mold or using a lasercutter to cut out the belt teeth with a compatible mateial.

For the testing of ZTM; the phase 1 tests were unsuccessful except for the range of motion, due to the dc motor used, which moved in only clockwise direction and did not possess sufficient torque. In phase 2 testing, the dc motor was replaced by a brushless dc motor (Castle Creations, SW4 Sidewinder, 3800kv), which had sufficient torque and speed. However, the resolution of the motor could not be tested as it did not have an encoder. Further testing needs to be carried out to determine the resolution that can be obtained by using this brushless dc motor.

There are some limitations to the prototype. The parts need to be manufactured within tolerances and better materials need to be used. This will eliminate the bending and interference of some of the control box parts. The timing belts used in the system are stretchable this limits the torque that can be transmitted by the dc motor to the CBC pieces as the belt teeth stretch and slip over the timing pulleys.

V. Conclusion

This paper presents a new method to control the SATA instrument in 5-DOF, which includes rotations of the three CBC pieces (inner, middle and outer CBC piece), linear translation of the middle CBC and the movement of the SATA instrument towards and away from the surgical site.

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