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The SATA-Drive: A Modular Robotic Drive for Reusable Steerable Laparoscopic Instruments

Tomas Lenssen, Jenny Dankelman, *Member, IEEE*, and Tim Horeman

***Abstract*— *Introduction:* Most robotic instruments and their drives still risk residual contamination due to cleaning complexities, rendering them limited reusable, and tend to have larger instruments than the 5mm laparoscopic standard. The novel steerable laparoscopic SATA-LRS uses modularity for cleanability and exchangeability. The SATA-Drive: a robotic driver designed for the actuation of a 3mm scaled version of the SATA-LRS is presented. *Methods:* A modular, expandable gear mechanism was designed to efficiently rotate and translate the instrument shafts. The 3mm SATA-LRS is controlled as proof. An user-experiment is conducted to test the (de)coupling of the instrument to and from the drive. *Results:* A video shows the SATA-Driver successfully articulating, rotating and grasping the end-effector. End-effector dis- and reassembly is possible in 36 (13 SD) seconds, while complete instrument coupling requires 28(8 SD) seconds and de-coupling requires 16 (7 SD) seconds. *Discussion:* A non-surgical robot arm, mounted with the SATA-drive has effectively been transformed into a system similar to robot assisted laparoscopy. The modularity of the drive's segmented build can easily be adapted and could benefit the adoption of future instruments. The SATA-LRS's cleanability features and its end-effector changes without disassembly are expected to benefit medical robotics. The 3mm SATA-LRS shows the instrument's potential for mini-laparoscopy.**

***Index Terms*—Driver, instrument, laparoscopy, RAS, SATA.**

I. INTRODUCTION

THE USE of robot assisted surgery (RAS) has been steadily increasing compared to laparoscopic surgery (LS) or open surgery [1]. RAS supports additional Degrees of Freedom (DOF) which restore tip control to the more natural 6-DOFs rather than the limited 4-DOFs of standard instruments in LS. These movements are controlled using the natural motions of the surgeon's hand while tremor filtration, scaling and a 3-dimensional view further improve the use of instruments during surgery [2]. Robot systems are capable of further articulating local movement of the end-effector such as wrist motion, grasping and additional functions. However these larger robotic systems have a considerable cost, both in purchasing and maintenance, as well as a dedication of OR space [3]. Secondly, the standard method of control of the enhanced DOFs compromises tensioned cables that increase internal complexity and prevent instrument disassembly for proper cleaning. Therefore, most articulating instruments are single-use or limited reusable and still cope with residual contamination [4]. Moreover, these cable systems also limit the size of the instruments used in RAS, regressing the laparoscopic standard to a larger diameter of up to 8mm. Though some 5mm instruments do exist, they often cannot steer or make use of multiple stacked segments to bend with long neck-like steering joints. These continuous bends have a radius of about 30mm and tend to be unstable. The new Shaft-Actuated, Tip-Articulated (SATA) instrument-line uses more compact and stable pin-joints able to bend in place.

The SATA instrument-line has initially been developed as hand-held instruments for arthroscopic and laparoscopic use, capable of steering its end-effectors with up to two additional DOFs [5], [6]. With an important design focus on the cleanability and re-usability of the instrument, the DOFs of the tip are articulated without the use of cables, and instead make use of mostly hollow structures. The end-effector and all shaft components can thereby be disassembled for explicit cleaning, inspection and maintenance, avoiding the necessity of advanced cleaning and sterilization equipment. Multiple manufacturers of conventional instruments for minimally invasive surgery recognize the trend toward more sustainable surgical solutions through re-use and modularity. Wolf [7], Storz [8] and Olympus [9], all manufacture instruments that can often be split in two or three parts: tip with push pull rod, shaft and handle. In robotic surgery however, the possibility to fully disassemble or re-use instruments is rare and only commercially seen in Asensus's Senhance system for the non-steerable instruments. In line with this capacity for disassembly, the instrument-line has also been developed in a modular form, allowing the use of multiple shafts and end-effectors on a single handle so that the specific instrument functions can be tailored to the surgeon's need in a procedure [10]. This ability of in-use tip-exchange could also help lower operation costs and time of robotic systems by reducing the number of active or stand-by arms.

The SATA-LRS (Shaft Actuated, Tip Articulated - Low Resource Surgery) instrument, in which almost all DOFs

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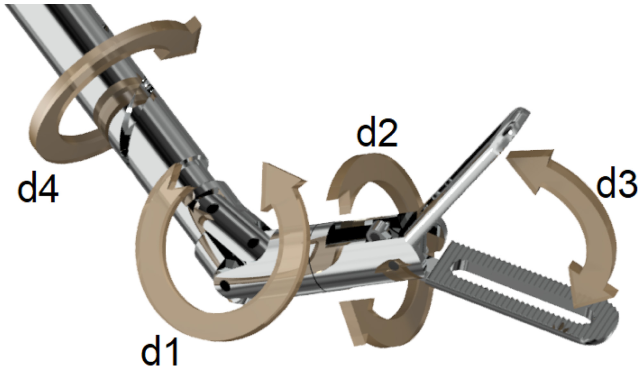

Fig. 1. Indication of the 4 DOF of the SATA-LRS end-effector. Respectively: articulation, rotation, grasping and axial orientation.

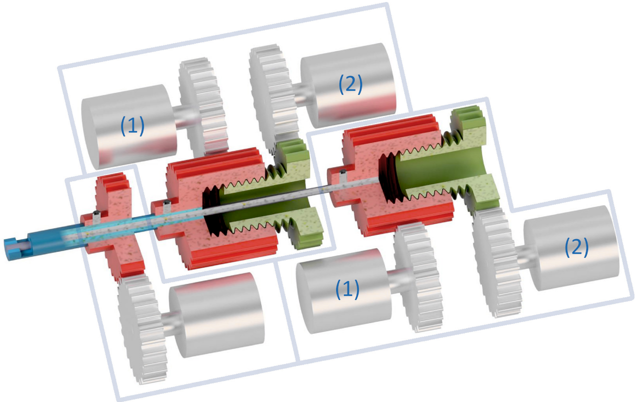

Fig. 2. A schematic model of the SATA-Drive, consisting of three instrument axes, two of which are actuated by a Screw-Rotation-Transition (SRT) which use two motors (1) and (2).

are rotation driven, is suitable for motor actuation, allowing conversion into a modular robot controlled system. This work describes the design and validation of a novel, modular SATA-Drive to actuate SATA instruments and enable them for use in robotics. As a proof of potency, the shaft, SATA-hinge and an end-effector of the SATA-LRS have been produced as a 3mm scaled copy and are used as a case-study for the validation of the driver and instrument. The so-called mini-laparoscopy (ML) category, in which instruments smaller than 5mm are used, has shown to be an effective and feasible alternative to general laparoscopy with minimal adaptation requirements, while patients enjoy cosmetic and pain improvements [1], [11]. ML could also be beneficial in pediatric surgery [12]. However, ML has so-far rarely been developed for steerable instruments in RAS. Recently, the company "Intuitive" developed a 3mm steerable instrument for the Da Vici robot system which was built and tested as a prototype [12]. The company "Asensus" have tested their Senhance robotic system with 3mm, non-steerable instruments in patients [13]. Last, the company "Medical Microinstruments" developed their 3mm Symani system for open-microsurgery [14]. Yet, insofar as these systems are steerable, they are all cable-driven. The work presented in this article aims to develop a steerable, cable-less, 3mm instrument and its modular robotic driver.

II. METHODS

A. Actuation of the Instrument

The previously developed SATA-LRS is able to actuate its end-effector in 3-DOFs: an articulation, a rotation and the grasping action of the tip [10]. Further steering actions come from a 4^{th} DOF in which the end-effector's articulation direction (see DOF d1 in Figure 1) can be steered using DOF d4: a rotation of the entire instrument. Rotation of the end-effector is achieved through rotation of its inner push-pull rod, which is also used to actuate the grasping motion by translation. The SATA-hinge, which articulates the tip, is similarly actuated through a set of pins translated by a grove cut-out in the rotating outer shaft in relation to a static inner shaft. The relation between shaft rotation and tip articulation is determined by the angle of the cut-out, which has been optimized for the 3mm scale. In order to create DOF d4, both the outer and inner shaft, as well as the push-pull rod, need to rotate simultaneously. The unique advantage of the SATA-LRS comes from the alignment of all these DOFs which are all achievable through simple rotations: the general output of standard electro-motors. Figure 2 shows the so-called Screw-Rotation-Transition (SRT) of a red and green gear pair. Two rotational motor inputs can differentiate into either the rotation or translation of the grasped shaft. Rotating (1) and (2) simultaneously will result in pure rotation of the axis, while rotating (2) with a stationary (1) will cause the axis to translate over the threading between the red and green components, without rotating. Using this simple gear transmission, the electro-motors can be placed parallel to the axes. Though the middle shaft currently only requires rotation, for the sake of future abilities a second SRT has also been applied to the middle shaft, allowing the middle and inner shaft to translate with respect to the outer shaft, effectively making the inverse relation as well. This makes the system use 5 motors to virtually generate a 6-DOF articulation output.

B. Modular Design and Shaft Connections

The SATA-LRS is able to disconnect its shafts from the handle for cleaning through the use of the Puzzle-Piece-Connection (PPC) [10]. The outer and inner shafts are connected to the drive in a similar fashion, with exception of the push-pull rod. To enable the independent exchange of the end-effector, the push-pull rod was given a quick-release system which enables the connection independently of the other shafts. The drive is build with three modules for the three instrument axes (see Figure 5). The outer shaft requires only rotation, while the inner shaft is given rotation and translation through an SRT. The push-pull rod of the end-effector is similarly given an SRT with the addition of the quick-release system. This modular build of the SATA-Drive allows it to stay lean by swapping modules to be tailored to the specific requirements of the instrument.

C. Robotic Parameters

Further design requirements for the driver to be fit for full robotic operations stem from its compatibility with a

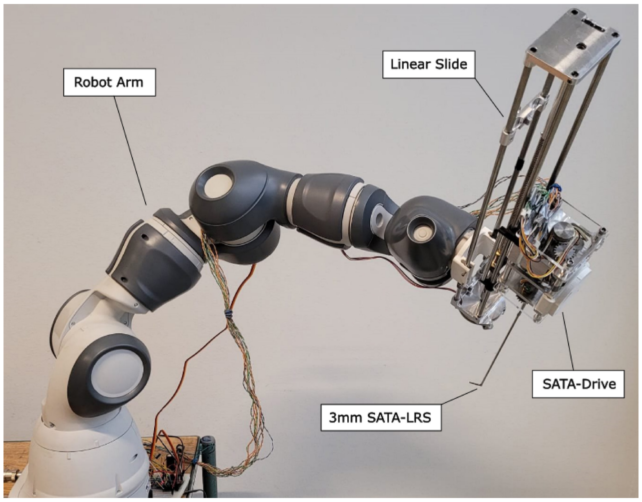

Fig. 3. Robot arm set-up for testing the SATA-Drive and the 3mm SATA-LRS.

robotic arm. As general size and weight have been considered important factors to minimize, custom build driving units were developed. Extra small stepper motors (GM12-15BY, TT Motors) have been selected to drive the system, which have the advantage of control precision, position maintenance, and feed-forward position control. The motors are fitted with local 1:99 ratio gearboxes to increase strength. The driver has also been designed to have multiple flange-sides for attachment.

D. Production of the 3mm SATA-LRS

The design of the 3mm SATA-LRS was done by direct scaling of all parts with exception of the so-called slider-pins and diagonal groves to prevent fragility as they carry the articulation transmission. All parts were produced using conventional CNC methods. The end-effector is partially produced out of a refurbished 3mm biopsy forceps cup jaw (OLYMPUS A4633), which is brazed to a flexible cable and push-pull rod. Assembly of the SATA-joint was aided by laser spot-welding.

E. 3mm SATA-LRS Technical Validation

The 3mm shafts and SATA-joint have been manufactured, assembled and combined with the custom made end-effector. Fitting of the components has been verified through an identification of slack and play between each connection. The mechanical movement of the SATA-joint has been verified using the SATA-Drive both with and without the end-effector. Total range of motion for the articulation and rotation have been tested, as well as push-pull rod stroke. Fitting of the shafts for (dis)assembly have been further verified through the application in the user experiment. General steering and grasping have been tested using the SATA-Drive aided by a 7-DOF YuMi IRB 14050 robotic arm (ABB Robotics) to outline the driver and instrument with a grasping task (see Figure 3).

F. Instrument (Dis)Attachment User Test

To examine the ease of use around the removal and placement of the 3mm instrument on the SATA-drive, the system has been configured statically with the PPC outlined by the motors. After viewing an 1:25 minute instruction video (see Video attachment 1), 8 participants (PhD candidates & master students, BME department, Delft University of Technology) were asked to remove the end-effector from the instrument shafts followed by the complete removal of the instrument shafts and hinge mechanism from the drive. Thereafter, the students were asked to reassemble the instrument in reversed order. The time to completion was noted for each of the two steps. In total, each participant was asked to repeat the dis- and reassembly seven times of which the last 3 repetitions are used to determine the final median time to complete the tasks. During the tasks the participants were allowed to ask for further instructions, or would be given instruction on erroneous assemblies, which were recorded.

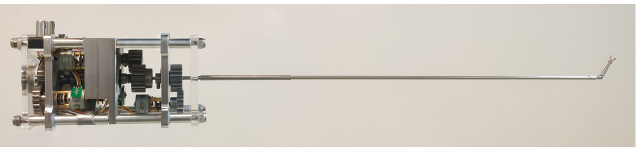

Fig. 4. A side view of the SATA-Drive holding the 3mm version of the SATA-LRS.

III. RESULTS

A. Mechanical Production

A prototype of the SATA-Drive and 3mm SATA-LRS have been successfully produced (see Figure 4). The driver is able to rotate all shafts independently, as well as translate the inner shaft and push-pull rod. The SRT system in the drive efficiently generates shaft translation from standard motor output rotation. Gear ratios between the shaft-locking gears and motor-locking gears have been kept 1:1 along a threading of pitch 1. At full speed each motor can turn an axis at 0,625 rotations per second, resulting in a push-pull rod translation of 0.625mm per second. This translates directly to an instrument rotation of 0,625 rotations per second and an articulation of 100° per second.

Each SRT mechanism is kept compact in an axial length of 50mm, and a radial length of 30mm in which two motors, four gears and the required frame are housed.

Using the Puzzle-Piece-Connection the two shafts of the SATA-LRS will be partially, semi-permanently assembled in the driver, allowing for quick (de-)coupling of the shafts for sterilization purposes, similar to the hand-held version in [10].

The push-pull rod is attached using a collet clamping system at the tail-end of the driver. This passive component is able to grasp the rod while simultaneously wedging itself into the transmission gear. Both grasping and releasing the rod requires about 2 seconds when actuated by the driver. The collet clamping system is able to effectively transfer translation and rotation to the push-pull rod, thereby actuating the end-effector.

The SATA-Drive weights a total of 604 grams and is kept small at a footprint of 12x6,5cm with a height of 6,5cm. All four radial sides are left blank as a flange-side and contain frame structures able to carry the weight of the drive without deformation. All gears, axes and bolts are made of steel, while

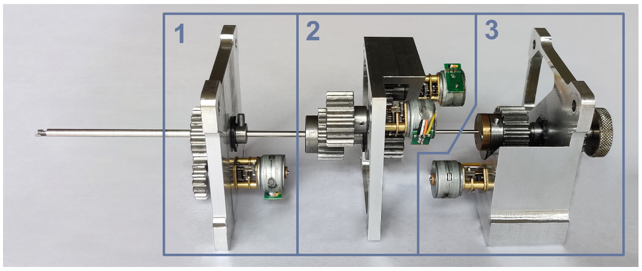

Fig. 5. The drive separated in its three modules.

the frame-plates are made of aluminium to reduce weight. The front and back covers are made of PMMA.

The 3mm version of the SATA-LRS shafts and joints have been successfully produced into a working instrument. The tip is able to articulate sideways 60° to 65°. Rotation of the end-effector is free, though this should be limited to 360°, similar as in [10]. Actuation of DOF d4, full instrument rotation, is infinite. Including the cup forceps, the distance from the tip-end to the point of articulation is 21mm. The SATA-LRS shafts and the forceps combined weigh a total of 11 grams.

B. Modular Build

Figure 5 shows the SATA-Drive separated in three modules. Though the drive has been built in this particular configuration, the design is entirely modular and supports different assemblies. Module 1 can rotate a semi-permanently attached shaft with PPC connection, which is used to rotate the outer shaft of the instrument. Module 2 consists of a SRT and is able to rotate and translate the inner shaft of the instrument which is again connected with a PPC. Module 3 consists of a similar SRT but has been fitted with the additional quick-release system for the push-pull rod of the end-effector.

C. Control

GM12-15BY stepper motors are controlled using an Arduino Nano micro-controller along with a set of DRV8825 stepper-motor drivers. Each motor has a precision of 18° per step, and is fitted with a local gearbox with ratio 99:1, offering a step per shaft-rotation ratio of 1980:1. The position-holding capacity of the stepper motors is used to keep the instrument non-backdrivable, although unpowered motors do allow this. This ability is also used during control of the SRT where both gears have to step antagonistically, or analogously, similar to DOF d4 actuation which requires all motors to step simultaneously. The accuracy of this system, unlike with DC motors, is not disturbed by resistances. Using step-counting from a known starting position the drive is able to align the shafts autonomously, specifically the PPC for (de)coupling. The system can furthermore keep track of axis rotations to prevent over reaching of certain DOF.

D. Technical Evaluation

The drive is able to fully actuate the SATA-LRS in all four DOFs as indicated in Figure 1. The SATA-drive has been successfully applied in a demonstration of which the video can be seen in Video attachment 2. All 4 DOFs of the instrument are articulated with sufficient precision and control for outlining, grasping and placing of the instrument and end-effector. Supported by a standard robotic arm the SATA-Drive can be partially outlined with a target, after which it can steer the local DOFs of the 3mm SATA-LRS. The demonstration shows the driver able to control the instrument as such that it captures a target object inside a 5mm tube set at an altitude and azimuth angle of 45° with respect to the approach direction, an image of which is shown in Figure 6. The demonstration video also shows the grasper hold and rotate a €1 cent coin with a diameter of 16.25mm, thickness of 1.67mm, and a weight of 2.3 grams.

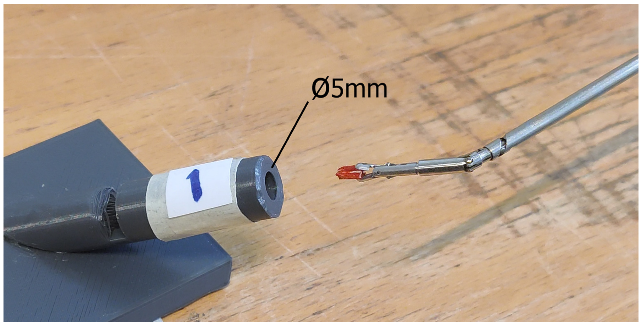

Fig. 6. A still from a demonstration video showing the 3mm SATA-LRS controlled by the SATA-Drive extracting a target body, supported by a robotic arm.

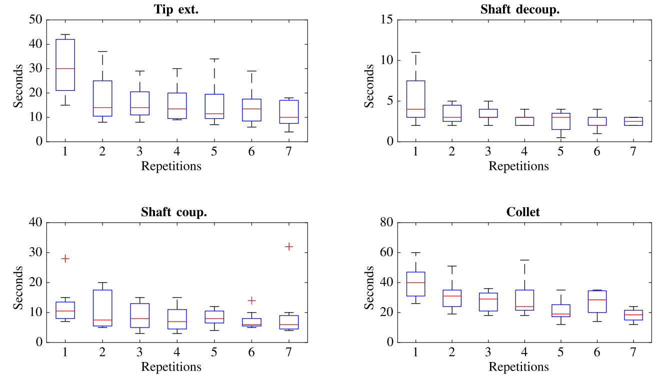

Fig. 7. A boxplot of the (dis)attachment study showing the time needed for tip extraction (upper left), shaft decoupling (upper right), shaft re-coupling (bottom left) and tip re-attachment (bottom right).

Furthermore, the demonstration shows the removal of the end-effector independent from the instrument's shafts, which are removed thereafter. The video shows removal of the end-effector within 15 seconds by untightening the quick-release collet system at the back of the drive followed by the unscrewing of the end-effector from the SATA-LRS. Removal of the shafts from the drive is shown to require 5 seconds.

E. Instrument (Dis)Attachment Validation

Figure 7 shows the boxplots for each task in the dis- and reattachment of the instrument to the driver. The top two plots show the extraction of the end-effector with its push-pull rod, before which the collet quick-release needs to be untightened, followed by the decoupling of the shafts from the driver. In reverse order the reattachment of the shafts and end-effector are shown in the bottom plots. Particularly the disassembly

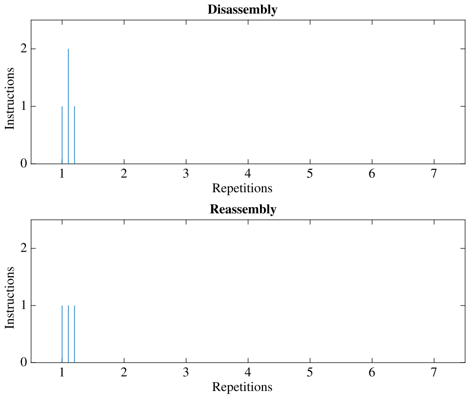

Fig. 8. A boxplot of the (dis)attachment study showing the participant's required instructions.

shows a large step in performance after the first interaction with the system. Shaft coupling shows some outliers which indicate difficulty with the PPC connection, though overall this feature showed no impedance to the task.

Using the average of repetition 5 to 7 of all participants the specific time required for tip extraction, shaft decoupling, shaft coupling and tip attachment, was respectively 13.6 (7.3 SD), 2.5 (1.0 SD), 7.0 (2.4 SD) and 22.2 (7.6 SD) seconds. Complete dis-assembly required 16 (7 SD) seconds, whereas complete assembly required 21 (6 SD) seconds. Using the participant's required time for end-effector extraction and re-insertion (tip-exchange), while having placed all disassembled parts on a table, the total shows a time requirement of 29 (10 SD) seconds. Instructions given additional to the preceding instruction video have been measured as well. Three participants required an instruction at first exposure to the task, yet all participants were completely independent at the second round.

IV. DISCUSSION

The hand-held SATA-LRS has been successfully actuated by a motorized, computer controlled mechanism able to govern the instrument's DOFs in a robotic sense. The SATA-Drive is capable of actuating the motion output of the SATA-LRS to the point of functionally grasping and manipulating objects in a robotic setting. Mounted on a robot arm, the drive has shown its potential for robot assisted surgery as a fully remote controlled robotic system. The 3mm scaled version of the SATA-LRS has proven adequate in performing tasks similar as in basic laparoscopy, and is thereby considered a viable instrument, and an appropriate representative of the original.

A. Mechanical Working and Control

The use of the SRT mechanics proved valuable not only in producing efficient translation out of motor rotation, but in their size efficiency as well. Overall, the SATA-Drive is kept compact and lightweight, though it could be further reduced by removing the second SRT system including a fifth motor. The current drive is large enough to potentially fit the original 5mm shafts of the SATA-LRS. However, with exception of the used motors, the design is entirely scalable to fit the 3mm version specifically, thereby reducing weight and size.

A remote controller was the only interface to control the steering, positioning and grasping of the instrument and drive combination. A completely feed-forward approach has been applied with a shared control through pre-programmed limitations and backtracking of steps for position alignment. So far, the drive lacks any position feedback sensors, yet the use of the stepper motors allowed for precise control of each gear in the SRT's which prevented drift. No concerning misalignments have been experienced. Though responsiveness was high, control velocity of the instrument was rather low. Concerning the motors, it might be noted that the maximal velocity of each axis could be improved using the same motors with a lower gear-ratio in their local gearboxes. In doing so, no torque consequences are expected as each motor's voltage can be increased from 9V to 12V and no force limitations have been observed. Gear backlash compensation by pre-emptive stepping was an added benefit of the stepper motors, and can be adjusted over time, although shaft-position feedback would improve this blind approach. Position feedback sensors in general should be considered for further application of the system in an environment that offers dynamic resistance. General wear of both the transmission gears and SATA-joint could jeopardize accuracy, although the latter has tight tolerances bellow 0.01mm in the pin cut-out, which could be improved with a surface contact rather than the current line contact.

The SATA-LRS uses a threaded chamber to both secure the end-effector and support its axial rotation. As such, rotation of the end-effector causes a slight parasitic translation which influences the push-pull rod position relative to the beak mechanism. This has earlier been reduced to a maximum translation of 0.5mm through the use of fine threading. Yet, using the SATA-Drive, the SRT mechanism controls both the rotation and translation of the push-pull rod, and is thereby able to fully compensate for this parasitic translation, increasing control over the instrument.

B. Modular Build

The current build is an assembly of thee individual modules each controlling up to two DOFs. These modules are entirely exchangeable, making the drive easily adaptable to a further diversity of end-effectors or instruments that have up to six DOF. Each module can also use different motors with different local gear ratios and strengths, specializing in precision or speed. Module 3, governing the end-effector, might benefit from a faster set of motors, for example. The independence of each module also allows electrical isolation which could support the use of bi-polar instruments in the future.

C. 3mm Instrumentation

The 3mm version of the SATA-LRS has proven to work as satisfactory as its 5mm predecessor in terms of motion, assembly and control. With a similar articulation range and equal end-effector rotation the control of the instrument is a copy of the instrument as in [10]. As such, this 3mm instrument is a suitable representation of the original hand-held SATA-LRS. The original instrument design was validated for numerous surgical tasks in both arthroscopy and laparoscopy [5], [6]. The tip components could withstand an axial load of 100N as well as a tangential load of 20N without damage [5]. It is assumed that the 3mm scaled version of the 5mm instrument has similarly scaled strength and capabilities, which is expected to be sufficient for tissue manipulation, needle driving and knot tying [15]. Nevertheless, different end-effectors should be developed, including needle-holders and scissors, to test its strength during multiple surgical actions like tissue manipulation, cutting and suturing. Similarly, the tip-end length can be improved. The final version of the 3mm instrument as a whole also requires further testing after optimisation of its shaft rigidity by choosing the best wall thickness of the tubes. The use of the 3mm biopsy forceps has shown that such end-effectors can adequately be controlled and used in this instrument-line. Pushing the SATA-LRS to a 3mm version will improve patient scarring, healing and pain, while the SATA-Drive has been shown capable of handling the smaller version with the required precision and control. It is expected that the original 5mm version can be driven with similar results.

D. (Dis-) and Re-Assembly

Removal, and exchange, of the end-effector is done in simple steps that require minimal human intervention. The quick-release system clamping the push-pull rod passively adapts to the depth and rotation of the end-effector during insertion, and grasps the rod with minimal effort through the collet mechanism. Active aid to this human intervention at grasping or releasing is also possible through the rotation of one of the motors of the drive. Disassembly of the shafts is done similarly as in the hand-held SATA-LRS through the outlining of the puzzle-piece-connection, which is now outsourced to the drive and requires only removal of the overlapping tube. Manual outlining of the shafts proved to require a substantial time-part in the (dis)assembly of the hand-held SATA-LRS, where the robotically outlined (dis)assembly experiment with the driver shows a major improvement. Dis- and reassembly times for the shafts and end-effector required 37 (12 SD) and 105 (56 SD) seconds for the hand-held instrument, compared to 16 (7 SD) and 21 (6 SD) seconds with the SATA-Drive. In spite of the smaller features of the 3mm instrument, interaction complexity was significantly reduced by the robotically pre-aligned puzzle-piece-connection and the driver acting as a stable platform. The required instructions additional to the instruction video proved minimal, with complete participant independence after a single try, indicating an intuitive design. The 29 seconds required for end-effector extraction and replacement promises a practical possibility for intra-operative instrument switches.

E. Robotic Actuation

The production of this driver is the first step to have the hand-held SATA-LRS directly exchangeable with a robotic system. As shown in the demonstration video, mounting the drive onto a robotic arm promptly enabled the instrument to perform robot controlled tasks similar as seen in RAS interventions. The ability to exchange instruments between hand-held handles and robotic systems could prove adaptive in unforeseen circumstances, and could reduce costs in instrument procurement, use and maintenance. The benefits of the SATA-LRS, which was designed for cost-reducing modularity, are now also applicable to the robotic setting. Including reusable instruments in surgical robotics has proven to be challenged by residual contamination. The SATA-LRS offers the unique ability to perform its articulation without the use of cables and is furthermore designed for disassembled cleaning and inspection. It is expected that these features could improve the current state-of-the-art of RAS.

Though the robotic arm used in this work is not rated for laparoscopic performance, it contains the right DOFs to steer the driver for such endeavor. The addition of the driver to the arm through a simple flange-connection has enabled the system to be used in ways similar as seen in surgical settings. Other robotics, similar to our demonstration, might be candidates for such conversion. Additionally, the ability of the SATA-LRS to change end-effectors independent of further disassembly might benefit the use of singular robotic systems which compete with large and expensive multi-arm systems. Similarly, the low weight of the drive and instrument enables the design of smaller, cheaper arms focused on simple frame dynamics.

Original LS is done with 4 DOFs of which the SATA-Drive is able to perform the axial rotation of the instrument. Extension of the SRT's could allow the driver to also control the instrument in axial direction within a limited workfield. Taking over this second DOF, that is currently outsourced to the arm, would reduce the required arm complexity to only two remaining DOFs outside the body.

F. Novelty

Comparing the drive and 3mm instrument to other known instrument-driver combinations on the market shows the value presented in this work. The company “Distalmotion” developed the Dexter robotic system that features a fully articulated 8mm instrument that uses cables and a unique slider interface between adapter and shaft. Although the instruments are single-use, their interface allows the instrument to contain fewer parts in an effort to be more sustainable, which shows their concern for the topic [16]. The company “Intuitive” developed the Da Vinci system which has the 5mm, steerable EndoWrist instruments that are semi-reusable (up to 14 times) through flushing. To manage the internal cables, each instrument comes with a gearbox attached which gets connected to the driver [17]. Three mm prototypes are in development, but these have a similar gearbox and are likely to have a similar number of re-uses and, due to limited space for cables, probably much weaker [12]. The company “Asensus” developed a line of 5mm modular, steerable instruments that operate without cables for robotic use. Though their non-steerable instruments are reusable through cleaning, their steerable instruments are not yet fit for cleaning and are disposables [18]. Recently, their focus also shifted towards non-steerable 3mm instruments [13]. The company “Micromedical Instruments” recently launched the Symani Surgical System as a 3mm robotic system for open microsurgery, which uses cables and is classified as disposable [14].

Comparatively, the SATA-Drive combines a cable-less, reusable, 3mm instrument with a modular driver able to adapt to the multiple DOFs as required by the instrument and to a certain surgical task.

G. Future Work

Apart from the technical validation of the instrument in this work, further feasibility and user tests are required to validate the instrument as a 3mm instrument for laparoscopy in a clinical setting. Possibly, applications such as open surgery, similar to [14], can be considered to reduce requirements on the shaft length and rigidity. Further developments of the SATA-Drive are planned in-line with the modular, cleanable design of the SATA-LRS. Similar to the disconnection of the shafts for sterilization purposes, following designs will focus on separating parts of the drive with direct contact to the instruments for sterilization, while leaving the motors and other electronics mounted as part of the robot arm. Secondly, a more adaptive coupling system should be applied to all shafts for dynamic assembly of different sized instruments.

V. CONCLUSION

A modular robotic drive for the hand-held SATA-LRS has been successfully designed, produced and tested as an exchangeable actuation method. The SATA-Drive is a lightweight, compact mechanism able to control the output motions of the SATA-LRS in a robotic sense. Combination of the drive with a robotic arm has demonstrated the potential of the drive not only to actuate the instrument functionally, but to extend the use of the SATA-LRS to the robotic world and its medical applications. The modular design of the SATA-LRS, focused on disassembled sterilization, inspection and repair, should be beneficial to the field of robot surgery. The SATA-Drive represents the first step to having this laparoscopic instrument-line as part of RAS intervention. A 3mm version of the SATA-LRS has successfully been produced and shown a suitable representation of the original hand-held SATA-LRS. Despite the early stage in development and need for further strength and functionality testing in a more relevant clinical setting, the 3mm instrument has been shown to functionally steer and grasp towards a hidden target at an angle and has features enabling exchangeability between robot and hand-held control.

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