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Article

Design and Validation of an Automatic Instrument Carousel Exchange System (ICES) for Robot-Assisted Laparoscopic Surgery with Modular Instruments

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Abstract

Background: Efficient and safe instrument exchange remains an important challenge in robot-assisted laparoscopic surgery (RALS). Current workflows require human assistance, increasing staff workload and contamination risk. The modular design of the AdLap robotic laparoscopic instruments enables automated exchange of instrument shafts. This study presents the development and validation of the Instrument Carousel Exchange System (ICES). **Methods:** An automatic ICES was developed for the AdLap robotic surgery platform of the Delft University of Technology. The prototype was designed to hold six Shaft-Actuated Tip-Articulating (SATA) modular instrument shafts (SATA instrument line, SATA Medical, Amsterdam, The Netherlands) and focused on compactness, robustness, modularity, and rapid disassembly for cleaning and sterilization. System performance was evaluated using repeated autonomous instrument exchange cycles without user interaction. Reliability, alignment tolerance, safety, and exchange duration were assessed. **Results:** The ICES prototype was successfully designed, manufactured, and tested. Repeated functional testing demonstrated reliable autonomous instrument shaft exchange without human intervention. The system tolerated minor alignment deviations while maintaining stable and safe operation. The mean time for a complete instrument shaft exchange was 84 s (SD = 10 s). The modular architecture allowed straightforward disassembly and maintenance while preserving structural integrity and compact design. **Conclusions:** The developed ICES represents a substantial step toward fully automated modular instrument handling in RALS. Automated instrument exchange may reduce staff workload and minimize contamination risk during procedures. Future work will focus on improving automation speed, alignment efficiency, and autonomous reinsertion of the instrument shaft through the trocar to further enhance clinical applicability.

Keywords: robotic surgery; modular instruments; exchange system; carrousel; laparoscopy; automatization

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1. Introduction

Robot-assisted surgery (RAS) represents a significant advancement in medical technology, enabling surgeons to perform increasingly complex procedures with the assistance of robotic systems. These systems are designed to enhance surgical precision and dexterity, resulting in reduced risks of complications, shorter recovery periods, and improved clinical outcomes [1]. Technologies such as the da Vinci Surgical System have seen widespread adoption in fields such as urology, gynecology, and oncology, highlighting their versatility and impact on patient care [2]. Despite these advancements, RAS faces notable operational challenges, particularly in relation to the high demand for skilled surgical staff and the sterility requirements of the operating room environment [3,4]. Current robotic systems rely heavily on human intervention for tasks such as instrument handling and trocar docking. This human interaction with the instruments increases the risk of contamination, which could adversely affect patient outcomes [5]. With increasing costs and skilled worker shortages, hospitals have difficulties with staffing the operating room with scrub nurses. This results in postponed surgeries due to lack of staff, longer waiting times and increased health risks for the patient [6].

Numerous studies have focused on minimizing the reliance on skilled personnel within the operating room, particularly through a robotic scrub nurse [7–9]. These systems identify the required conventional laparoscopic instruments through prediction models, gestures or verbal commands and provide them to the surgeon. Some systems even partially insert the instrument in the trocar [10]. Although much of the research has been focused on laparoscopic surgery, the instrument selection and partial trocar insertion can potentially also be applied to robot-assisted laparoscopic surgery (RALS).

Automatic instrument exchange implementation in RAS has different challenges depending on the subset of RAS. Within the field of microsurgery for ocular applications, several studies present fully automated instrument exchange [11,12]. Whithin RALS, adaptable tool heads have been suggested rather than replacing entire instruments [13]. Carousel systems were also proposed and tested to present a Da Vinci instrument to an intermediate (scrub nurse) [14]. The design of the Da Vinci systems, with all range of motion targeted around the trocar, prevents the arms from moving to a nearby carousel independently.

The AdLap project aims to develop a fully modular "waste free" RALS platform [15]. This platform makes use of 7-DOF robotic arms and reusable 5 mm steerable instruments [16]. The system is inherently modular, allowing individual components to be exchanged independently (Figure 1). This modularity offers several advantages, including simplified cleaning, targeted repair or replacement of worn components, and improved cost efficiency, resulting in a more sustainable product. Existing proposals for automated exchange systems in RALS have not yet utilized modular robotic instruments, leaving a clear gap for solutions tailored to component-level replacement.

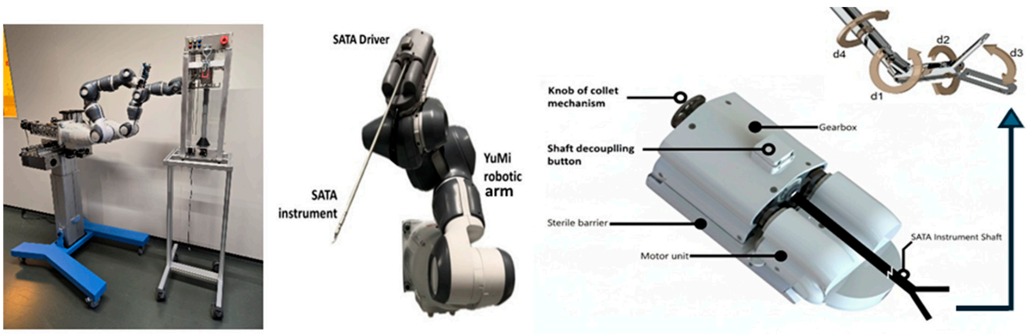

Figure 1. (**Left**) In situ visualization of the AdLap slave system. (**Middle**) Close-up of a single arm with driver and instrument. (**Right**) The AdLap end effector consisting of the driver and instrument.

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Novelty Statement

The Instrument Carousel Exchange System (ICES) presented in this paper is designed to automatically exchange and store Modular SATA instrument shaft components of the AdLap RALS system, with the ultimate goal of eliminating the need for human instrument handling during surgical procedures.

2. Methods

The AdLap system (v2024, Delft University of technology, Delft, The Netherlands) operates with fully reusable laparoscopic instruments called Shaft-Actuated Tip Articulating (SATA) instruments (SATA instrument line, SATA Medical, Amsterdam, The Netherlands). The 4-DOF instruments are driven by a newer generation of the SATA driver [17]. In line with the modular nature of the instruments, the end effector is designed to be robotic platform independent (Figure 1 Right). In the current setup two robotic arms (YuMi IRB14050, ABB, Västerås, Sweden, v2024) are used to position the instruments (Figure 1 Left). The instrument shaft is driven through a gearbox that is connected to the motor unit. The instrument shaft and gearbox are connected via two coupling mechanisms that are designed to be operated by hand (Figure 2). The collet mechanism clamps the inner shaft of the instrument and transmits rotational motion and translation of the shaft. The shaft decoupling button locks two slots coupled to the external and middle shafts of the instrument, enabling articulation of the tip through shaft rotations. When pressed, the button decouples these shafts, allowing insertion or extraction of the instrument shaft, provided the collet is loosened. As it is possible to manually assemble and reassemble the instrument assembly with 60 s, the ICES is expected to perform equally fast [17].

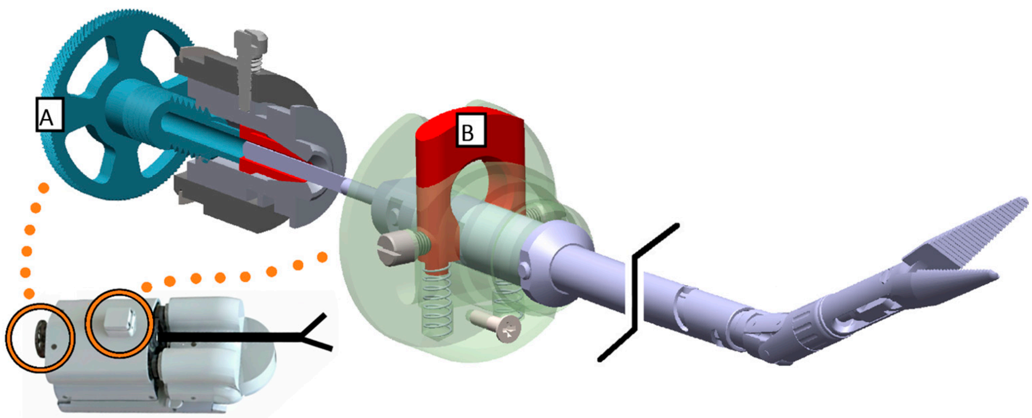

Figure 2. The inner coupling mechanisms of the SATA gearbox. When the blue collet screw at A is tightened into the base, it pushes the red collet gripper. The collet gripper is pushed along a slanted edge and clamps down on the inner shaft of the SATA instrument [18]. At B we see the shaft decoupling button in red. The spring-loaded button engages with the shaft to transmit rotational motion for the actuation of the SATA instrument. Additionally, the button locks the shaft in the SATA gearbox, and pressing it disengages the lock, allowing the shaft to be extracted [19].

The instrument shaft exchange in the AdLap system follows a defined sequence of steps to remove and replace SATA instruments. Figure 3 visualizes the interactions between the instrument shaft, SATA driver and ICES to exchange an instrument shaft. A and B show where the manipulation actions of Figure 2 take place.

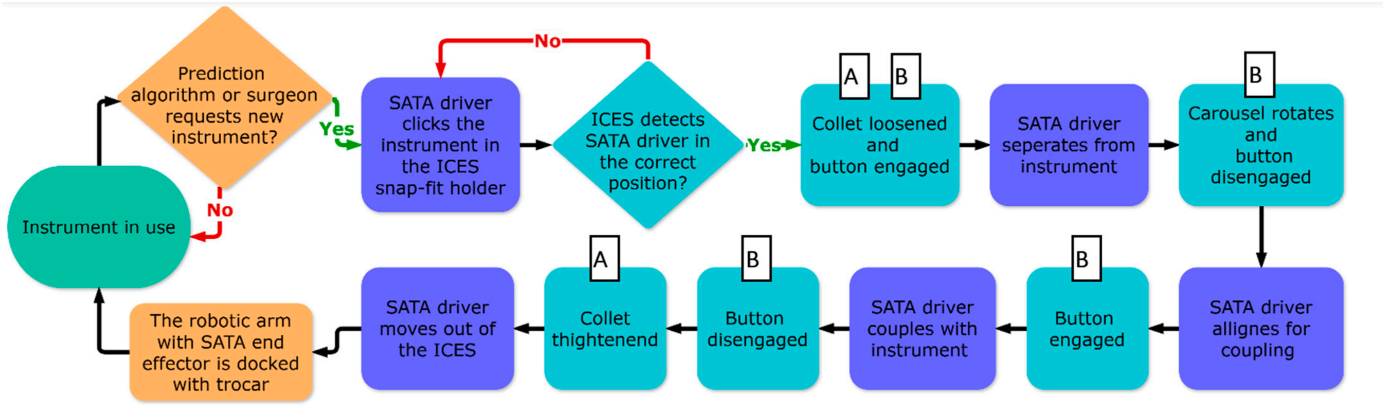

Figure 3. Flowchart of the SATA instrument shaft exchange process. The teal steps are ICES operations, and the blue steps are movements of the robotic arm with the SATA driver. When a change is triggered, the robotic arm moves the instrument to the exchange position, and the ICES verifies alignment. The ICES loosens the collet (A) and engages the decoupling button (B), allowing the robotic arm to separate the driver from the instrument shaft. A new instrument shaft is presented, after which the robotic arm docks the driver with the shaft. The button is disengaged to lock the shaft, the collet is tightened and the instrument returns to operational use.

2.1. The Design Process

During RALS with this system, the workspace around the patient is highly constrained, as the anesthesiologist, scrub nurse, surgical assistant, and robotic system all require proximity to the operating field. This limited space restricts the possible placement of an instrument shaft exchange system and leads to the preference of a system with limited dimensions. The mechanical configuration and surgical staff define the operational workflow of the AdLap platform, leading to several functional requirements and performance criteria. The functional requirements, as seen in Table 1, guide the design of the instrument shaft exchange system by defining the essential tasks the system must perform and setting the framework for its design. The performance criteria complement this by enabling the systematic evaluation of the concepts generated later in the process. These criteria are applied in a Harris profile to assess the design concepts and support a weighted decision regarding which concept should be developed further. The full list of requirements and criteria as well as the full design process, including concept selection and evaluation, can be found in Supplemental File S1.

Table 1. Functional requirements of the instrument carousel exchange system.

Requirement	Acceptance Criterion	Verification	Result
Performance			
Instrument exchange speed	≤60 s between first and last contact with the snap-fit	Instrument exchange cycle test [N = 10]	84 s (SD = 10 s)
Functional instrument exchange	Instrument is functional after the exchange and can exert >5 N pinch force	Collet force test	5.4 N (SD = 0.3 N)
Instrument selection	All instrument exchanges can be initiated using the ICES control buttons	Functional test	Pass
Instrument capacity	Hold at least five instrument shafts	Physical inspection	6 shafts

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Table 1. *Cont.*

Requirement	Acceptance Criterion	Verification	Result
Instrument alignment tolerance	Shaft alignment within 1 mm and 0.5°	Instrument exchange cycle test with deviations (1 mm and 0.5°) from alignment	Pass
Durability	Maintain functionality after at least 100 insertion/removal cycles	Snap-fit force test after repeated cycling	Functional after >100 cycles; reduced retention force observed
Robot positioning detection	Detect correct robot position before instrument (de)coupling	Instrument exchange cycle test (N = 10)	Pass
Design			
Portability	Can be carried by one person and assembled within 5 min	Assembly/disassembly test	Pass
Manufacturing cost	≤€1000	Design review	€975
Sterile field management	Compatible with international sterile field management principles	Design review/physical inspection	Pass *
Safety			
Manual instrument removal	Instrument shaft removable with <30 N extraction force	Snap-fit force test	16 N (SD = 3 N)
Emergency stop	Immediate shutdown of the ICES upon emergency stop activation	Functional test	Pass

* Compatibility with sterile field management was assessed at the design level and constituted inspection by an expert that concluded the 5 contact points could be cleaned properly. Sterility validation and regulatory compliance were outside the scope of this study.

2.2. Final Concept

From the three promising concepts in Supplemental File S1, the durability concept stood out in speed and feasibility and was therefore selected to be developed into a prototype. The design can hold up to six instrument shafts (Figure 4). In alignment with the sustainability goals of the AdLap platform, the design can be (dis)assembled with generic tools. Components can easily be remanufactured and are designed to be sterilized. Supplemental File S2 provides all details of the ICES and its sub-functions.

2.3. Testing Protocol

Various testing protocols were used to evaluate whether the prototype meets the defined functional requirements seen in Table 1. Additionally, some requirements are validated through expert observations or documentation rather than formal testing. A comprehensive overview of all requirements, acceptance criteria, and verification methods is provided in Supplemental File S1. The following tests were conducted in our lab setting: (1) (dis)assembly test, (2) instrument shaft exchange cycle test, (3) collet force test, and (4) instrument shaft snap-fit force test. All experiments were performed by a single trained operator, who was also involved in the design and development of the ICES.

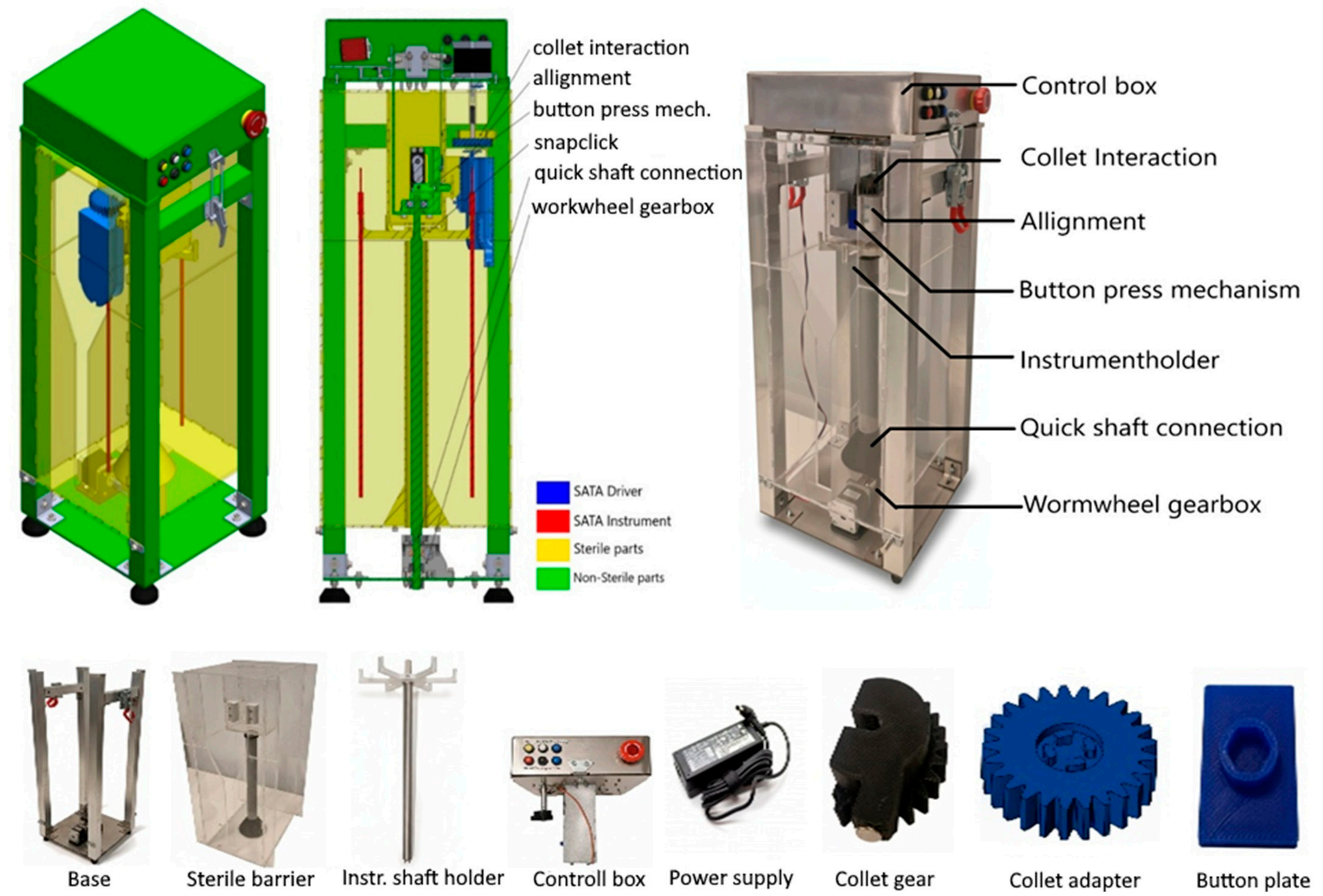

Figure 4. (**Left**) SolidWorks model (v2024) of the Instrument Carousel Exchange System (ICES), shown in both an isometric view and a cross-section view; the cross-section highlights the placement of seven critical sub-functions, including electronics, collet interaction, Alignment, button press mechanism, quick shaft connection and the worm wheel gearbox. Components are color-coded according to the legend: blue (SATA driver), red (SATA instrument shaft), yellow (sterile components), and green (non-sterile components). (**Right**) The realized ICES prototype. (**Bottom**) The individual components of the ICES prototype when disassembled.

(1) (Dis)assembly test

The installation test evaluated whether the ICES can be safely assembled and disassembled in the correct order within the required five minutes. All individual components of the ICES and SATA instrument shafts were placed on a table, and the timer started when the first part was picked up. After the ICES had been assembled and powered on, the system performed an automatic startup routine. Once the routine was completed, the SATA instrument shafts were installed using the dedicated installation tool to ensure correct orientation. The timer ended when the last SATA instrument shaft was installed. The detailed steps of the assembly process are explained in Supplemental File S3.

(2) Instrument exchange cycle test

The main objective of this test was to demonstrate that the robotic arm with the SATA driver can successfully exchange an instrument shaft with the ICES without any errors. The functional requirements specify that the exchange cycle must be completed within 60 s and that the ICES can detect if the robotic arm is correctly positioned for an instrument shaft exchange. The system should still be able to receive an instrument even if the docking is offset by 1 mm or misaligned by 0.5° in orientation. For the test, a predefined step pattern was programmed into the robotic arm using ROS 2. The ICES followed its own sequence during the exchange. Both sequences were manually triggered, with the robotic arm executing five steps per exchange and the ICES completing five steps, as seen in Figure 3. The ICES verified the position of the robotic arm with the SATA driver after each step using ToF sensors. The exchange cycle timing was measured from the moment the instrument shaft first contacted the carousel until it was fully removed from the snap-fit. The complete sequence was repeated six times under normal conditions and additionally twice with carousel rotation misalignments of approximately 0.5° in both directions and twice with 1 mm shifts in the entire ICES to the left and right.

(3) Instrument shaft snap-fit force test

This test was designed to verify the safety functional requirement related to manual instrument removal, which states that instruments can be manually removed from the carousel using less than 30 N of force. To ensure consistent force distribution and prevent removal at an angle, a small tool was developed to apply the force perpendicular to the instrument. The force required to insert or remove the instruments was measured using a spring balance (Figure 5). Five insertion and five extraction force measurements were performed at each of the six snap-fit locations and recorded by a camera to capture the maximum force value.

(4) Collet force test

This test evaluated if the collet provided a sufficient clamping force without slipping for proper actuation (pinching) of the instrument's jaws. The pinching force at the instrument's jaws was measured directly with a load cell (LSB201, Futek, Irvine, CA, USA). The measured pinch force before slip relates directly to the strength of the collet-shaft connection after the ICES tightened the collet. The test was terminated when no further increase in the measured force was observed despite incremental closing of the instrument jaws. The test was repeated five times to obtain an average maximum pinching force, with the collet loosened and tightened by the ICES between each trial.

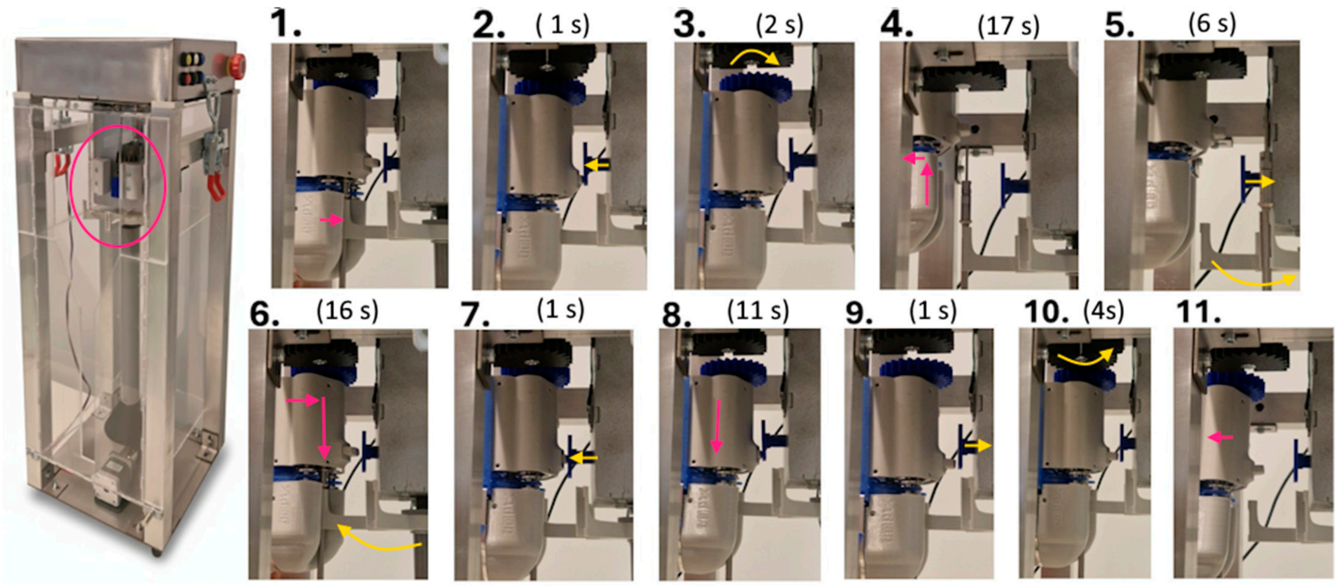

Figure 5. *Cont.*

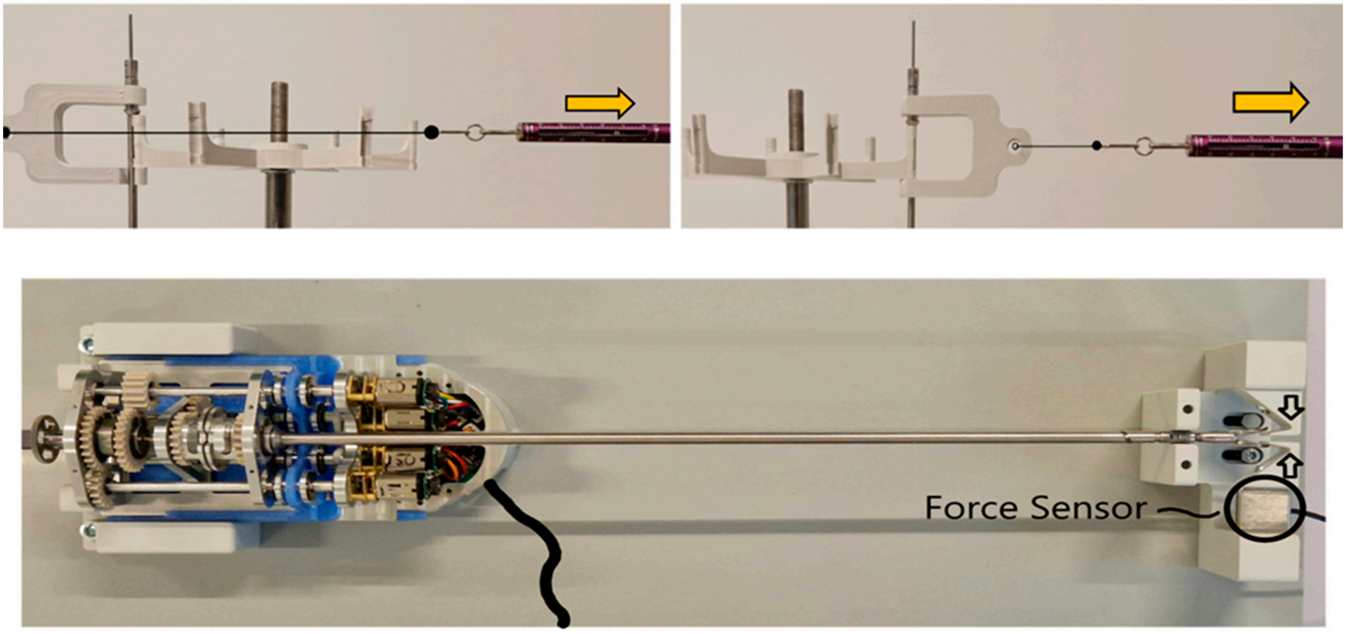

Figure 5. (**Top**) Sequential view of the instrument shaft exchange cycle of the Instrument Carousel Exchange System (ICES) with average step time. The pink circle (Top-Left) indicates the location of the relevant actuators and sensors. Steps 1 and 11 depend on the path the instrument must travel and are not constant. The yellow arrows show the movement of actuating components on the ICES side, and pink arrows show the movements of the instrument components. (**1**) The robotic arm docks the instrument shaft into the snap-fit. (**2**) The button mechanism pushes the button in, and the collet mechanism rotates to release the collet. (**3**) The collet mechanism rotates out of the way. (**4**) The robotic arm moves upward and away to release the instrument shaft. (**5**) The instrument carousel rotates to the next instrument shaft, and the button mechanism retracts. (**6**) The robotic arm moves halfway down toward the new instrument shaft. (**7**) The button mechanism pushes the button in again. (**8**) The robotic arm moves fully downward into position. (**9**) The button mechanism releases the button. (**10**) The collet mechanism locks the collet by rotating until three steps are skipped. (**11**) The instrument shaft is fully installed, and the robotic arm can move away. (**Middle**) Experimental setup used to measure the pulling and pushing forces with a spring balance. (**Bottom**) Experimental setup for measuring the pinching force at the curved Maryland tip to verify collet clamping strength. The instrument shaft is actuated by the SATA driver (driver shown on the left) while an LSB201 force sensor on the right records the pinching force. The collet clamping strength is evaluated as the maximum pinching force at the tip before slip occurs.

3. Results

A prototype of the automatic ICES was developed and successfully tested. An overview of the complete assembly is shown in Figure 4. The ICES enables automated exchange of SATA instrument shafts without human intervention. The carousel accommodates six instrument shafts and completes a full exchange cycle in approximately 84 s. Manual operation is possible via six control buttons on the device's housing, and an emergency stop button ensures the operator's safety. The ICES is fully modular, allowing it to be disassembled and reassembled in eight steps, which facilitates maintenance, cleaning, and rapid replacement of components. An acrylic sterile barrier around the carousel prevents the sterile shafts from contacting non-sterile objects. The shafts are placed in the carousel with a special tool before the surgery. The overall dimensions of the carousel are 250 × 250 × 720 mm, with a total weight of 13 kg.

3.1. Hardware and Manufacturing

All custom components of the ICES were produced in-house at the Faculty of Mechanical Engineering at TU Delft and off-the-shelf components were incorporated where appropriate. The gears of the collet mechanism, the two alignment blocks, the button-pressing attachment with servo bracket and the snap-fit holders are all 3D-printed in PLA. The frame of the ICES was constructed from 30 × 30 × 2 mm aluminum, 3 mm laser-cut acrylic, a stainless-steel baseplate and stainless-steel control box on top. The commercially sourced internal gears that drive the carousel have a 40:1 ratio for a high positional accuracy of 0.045° per stepper pulse. The ICES is powered by a 12 V/3 A power supply and controlled by an Arduino Mega2560 (Arduino Mega 2560 Rev3, Arduino, Ivrea, Italy).

Carousel and collet rotation are actuated by two stepper motors (NEMA 17, 0.49 Nm, 1.68 A, OMC Corporation Limited, Nanjing, China), while button actuation is performed by a servo motor (TD-8120MG, TianKongRC, Huizhou, China). The stepper motors are driven by two TMC2209 motor drivers (TRINAMIC Motion Control GmbH & Co. KG, Nuremberg, Germany) mounted on a CNC Shield V3 (Protoneer, Auckland, New Zealand). The TMC2209 drivers were selected for their integrated StallGuard functionality, which provides real-time load and stall detection. This feature is used to achieve reliable and repeatable locking of the SATA gearbox collet, ensuring sufficient clamping force for effective transmission of actuation forces.

The ICES is equipped with two Hall-effect sensors (DRV5033, (Texas Instruments, Dallas, TX, USA) and two time-of-flight (ToF) sensors (VL6180, STMicroelectronics, Geneva, Switzerland). The Hall sensors are used during system initialization to calibrate and establish the zero positions of both stepper motor shafts. The ToF sensors are employed to detect the position of the SATA driver during the instrument docking procedure, ensuring that operations are executed only when the driver is correctly aligned. One ToF sensor is positioned above the button actuation mechanism, while the second is located above the target collet position used during instrument shaft exchange. A full overview of the electronics and code is available in Supplemental File S4.

3.2. (Dis)assembly Test

The installation time test was conducted five times following the eight-step assembly procedure using the designer as the participant. Across these trials, the instrument carousel assembly process required an average of 188 s (SD = 30 s), with recorded times ranging from 165 to 242 s. In contrast, disassembly was completed more rapidly, requiring an average of 59 s (SD = 5 s) and ranging from 52 to 65 s (Figure 6A,B).

3.3. Instrument Exchange Cycle Test

The system was able to exchange instrument shafts automatically ten repeated times without failure (Figure 5 top). The exchange time took on average 84 s (SD = 10 s) with times ranging from 72 to 104 s. No manual interactions or software corrections were needed (Figure 6C). The 4 cases where slight misalignment occurred between the lodging parts did not add issues to the docking sequence.

3.4. Instrument Shaft Snap-Fit Force Test

The snap-fit force test was conducted without failure on all six instrument shaft locations, with each position measured five times for both pushing and pulling actions (Figure 5 middle). The average pulling force across all snap-fit holders was 16.0 N (SD = 3.0 N) (Figure 6E), and the average pushing force was 14.5 N (SD = 2.8 N) (Figure 6F).

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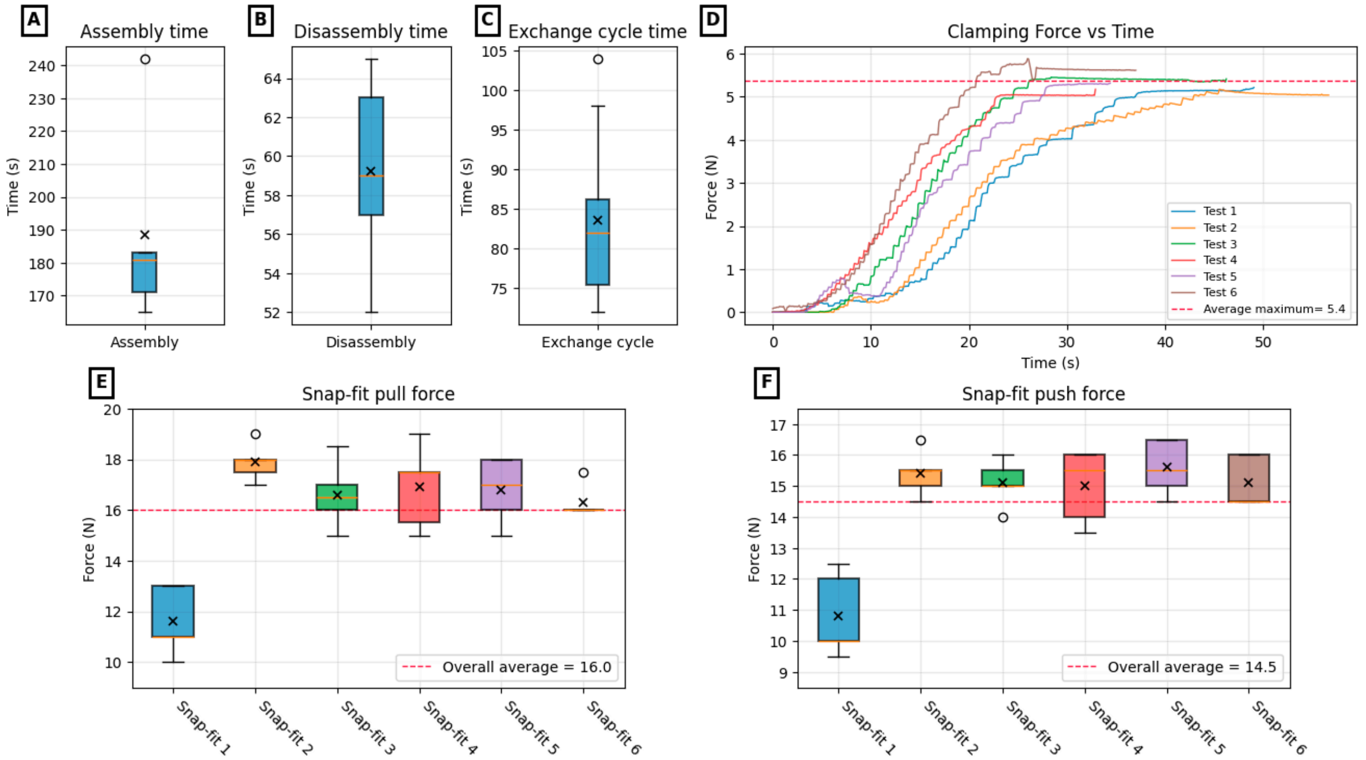

Figure 6. (**A**) Boxplot of the assembly time of the complete ICES over five trials. (**B**) Boxplot of the disassembly time of the complete ICES over five trials. (**C**) Instrument exchange time for ten executive instrument shaft replacements on the mounted gearbox. (**D**) Curved Maryland tip pinching force of the SATA instrument measured over time for six usable trials. The force was increased manually in discrete steps until the force measurement showed no more increase for approximately 10 discrete steps. (**E**) Box plot of the puling force measured for each snap fit holder over five trials per position. (**F**) Box plot of the pushing force measured for each snap fit holder over five trials per position. In the Box plot's of (**E**) and (**F**), the "o" represents outliers and the "x" mean values.

3.5. Collet Force Test

The collet force test was conducted six times without failure (Figure 5 bottom). The progression of pinching force over time is shown in Figure 6D. During each trial, the SATA instrument jaws were incrementally closed in discrete steps until no further increase in the measured force was observed, resulting in a stepwise force profile. The average maximum pinching force achieved was 5.4 N (SD = 0.3 N) with a range of 5.2 to 5.9 N. Subsequent investigations indicated that this force limit was imposed by the motor drivers' current protection mechanism, which caused the SATA actuators to stall to prevent damage to the motor unit. This interpretation was supported by manual pulling tests that demonstrated that slippage did not occur under applied loads of up to 15 N.

4. Discussion

This study shows that automated modular instrument exchange for robot-assisted laparoscopic surgery (RALS) is technically feasible using the developed Instrument Carousel Exchange System (ICES) integrated with the AdLap robotic platform. The ICES successfully enabled autonomous exchange of six reusable SATA instrument shafts without human intervention while maintaining stable and reliable operation throughout repeated testing cycles. The system demonstrated tolerance to minor alignment deviations, reliable collet engagement, and safe instrument handling, while preserving a compact and modular design that allows rapid disassembly, sterilization, maintenance, and component replacement. Repeated autonomous instrument exchanges were completed successfully with a mean exchange time of 84 s. Importantly, this study demonstrates the feasibility of combining modular reusable robotic instruments with automated robotic workflow support, representing an important step toward more intelligent and workflow-integrated robotic surgical systems. An overview of all functional requirements, their verification method, and whether the requirements were met is provided in Table 1. Observations confirmed that all contact points can be cleaned properly and the manual control interface functioned as intended.

The average instrument exchange time shows that the current setup is functional but does not reach the desired threshold of 60 s. The exchange time varied between 72 and 104 s, largely due to delays associated with manual operation of the control buttons between process stages. Direct communication between the systems could enable fully autonomous operation, resulting in more consistent performance and shorter exchange times by eliminating these delays and reducing the risk of operator error. To implement this, the ICES could be integrated in the ROS2 communication layer of the AdLap platform. An instrument exchange controller would require coordinated control of the robotic arm, the SATA driver, and the ICES. Hardware interfaces for the robotic arm and SATA driver are already available within the platform. Given the current ICES functionality, integration could be achieved by implementing a dedicated ROS 2 service node that exposes the instrument exchange operations. This would enable an exchange controller to invoke the ICES as part of a coordinated instrument exchange sequence. Another factor that could improve the overall exchange time is increasing the movement speed of both the robot and the carousel. These motions were kept at conservative speeds during testing to ensure safe operation.

The instrument carousel has proven to be robust, as all exchanges were completed successfully, including four cases where slight misalignment was created between the calibrated end effector position and the ICES. This shows that the mechanical tolerances and guiding features are sufficient to handle small positioning deviations without failure. Even though these deviations were allowed, setting up the robot in alignment with the ICES still takes several minutes. Active self-calibration when dealing with larger misalignments could speed up setup times since positioning will need to be less precise. Adding more TOF sensors or a camera would allow the system to compensate for misalignment with the predicted position. This would also require integration of the ICES in the ROS2 communication layer of the AdLap platform.

The collet force test showed that the instrument achieved a pinching force of approximately 5N. However, the actual pinch force could be much higher, as it turned out that the instrument shaft does not slip in the collet, but the drivers were currently limited to prevent damage to the SATA motor unit. This was confirmed with the extra pulling test with 3 instruments that showed that slip did not occur below a load of 15 Newton.

A significant portion of the installation time was spent installing each instrument shaft individually into the holder by cycling through all the slots. This process accounts for nearly half of the total time and could be significantly reduced by preloading the instrument shafts into the holder before assembly.

The snap-fit tests revealed reduced retention forces for one snap-fit location compared with the others. This difference is likely attributable to material fatigue of the 3D-printed PLA component, as this snap-fit position had been extensively used during development and subjected to more than 100 shaft insertion cycles. The snap-fit mechanism is one of the most mechanically demanding components of the ICES, as it undergoes repeated deformation during instrument insertion and retrieval while also resisting forces applied by the robotic arm. Future iterations could improve durability and consistency by employing materials with greater toughness and elastic deformation capabilities, such as ABS or PETG, instead of PLA.

Beyond the technical feasibility demonstrated in this study, the ICES may have broader implications for future robotic surgical workflows and operating room automation.

4.1. Clinical Workflow Implications

Automated modular instrument exchange systems may have important implications for future operating room workflows and staffing models in RALS. Current robotic procedures remain highly dependent on experienced scrub personnel, while operating room staffing shortages continue to increase worldwide. Recent robotic scrub nurse systems have demonstrated the feasibility of AI-driven instrument anticipation and automated instrument delivery during minimally invasive surgery [7–9]. In parallel, increasing evidence shows that workflow disruptions during robot-assisted surgery may negatively affect procedural efficiency and operative flow [20,21]. In this context, automated exchange systems, such as the ICES, could facilitate further automation of instrument management and exchange. By automating the exchange process, the ICES inherently reduces direct human handling of surgical instruments during exchange procedures. This may contribute to workflow standardization and could reduce dependency on specialized scrub nurses. However, the impact of such systems on contamination risk, staffing requirements, workflow efficiency, and clinical outcomes remains to be evaluated in representative clinical settings.

4.2. Sustainability and Modular Robot-Assisted Laparoscopic Surgery

An important strength of the ICES concept is its alignment with emerging sustainability goals in robotic surgery. Current RALS platforms mostly rely on disposable components and limited life instruments, contributing substantially to medical waste and procedural costs [22]. In contrast, the AdLap platform and ICES are based on reusable modular components that enable selective replacement, repairability, sterilization, and refurbishment of individual parts rather than complete instrument disposal. Previous work has already demonstrated the feasibility of reusable SATA instruments and modular robotic drivers with integrated sensing capabilities [17]. As healthcare systems increasingly prioritize environmentally responsible innovation, modular robotic systems may become increasingly relevant for sustainable minimally invasive surgery [16].

4.3. Autonomous Robotic Surgery Ecosystems

Beyond automated instrument exchange alone, the ICES may represent enabling infrastructure for future semi-autonomous and autonomous robotic surgical ecosystems. Integration with ROS2 communication, sensor-based positioning, computer vision, and AI-driven workflow recognition could facilitate coordinated robotic workflows with increasing levels of autonomy. Recent studies on robotic workflow recognition, autonomous task planning, and automated instrument insertion demonstrate the growing convergence of robotics, machine learning, and surgical workflow automation within the operating room [10,23–26]. Furthermore, broader frameworks describing levels of autonomy in surgical robotics increasingly identify workflow coordination and task automation as key enabling technologies for future autonomous surgical systems [27]. In this context, the ICES, which automates a supporting workflow task that is currently performed manually, may be viewed as foundational infrastructure for future intelligent and interconnected robotic operating rooms in which robotic systems autonomously coordinate both surgical manipulation and surrounding procedural logistics.

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4.4. Safety and Risks

In addition to the potential benefits, the introduction of an ICES introduces new technical and operational risks that must be carefully considered; these include system reliability, fault detection, and recovery from unexpected operating conditions. Future implementations intended for clinical use would require robust monitoring and fail-safe mechanisms to ensure safe operation and timely identification of exchange failures. Failure of the system to complete an instrument exchange could interrupt the surgical workflow and require immediate human intervention. To mitigate this risk, the SATA instrument and driver retain their original manual functionality, and the ICES was designed and tested to allow rapid manual release and retrieval of instrument shafts. Consequently, qualified operating room personnel would still be required to remain available during procedures, with the primary role of the ICES being to reduce rather than eliminate manual instrument-handling tasks.

Sterility also remains an important consideration. As the ICES introduces reusable components into the instrument exchange process, compliance with applicable sterilization and infection-control requirements must be demonstrated. While automation inherently reduces direct human handling of instruments during exchange, the overall impact on contamination risk and sterile workflow management remains to be evaluated in representative clinical environments.

4.5. Limitations and Future Work

We have demonstrated the feasibility of an ICES in lab settings. The SATA instrument shafts are certified for handheld use in laparoscopic surgery, but the AdLap System is not validated or certified for RALS operations. Further validation should include mock operations and full workflow integration tests.

Some components were deliberately over-engineered to ensure reliable functionality, resulting in a system heavier than necessary. Further weight reduction could improve handling and installation in a clinical setting. In addition, the current prototype lacks a clear status interface, making it difficult for the surgical team to identify whether the system is ready for instrument exchange or if an error has occurred. Integrating status indicators on both the ICES and the main console could improve usability and safety. Another important step toward improving performance is integration of the ICES with the broader robotic platform communication architecture. During testing, both the carousel and robotic arm operated at conservative speeds to ensure safe and controlled conditions. Direct communication between the systems would enable coordinated motion, potentially improving exchange speed, workflow efficiency, and operational safety by reducing unintended or conflicting movements. Future iterations may also benefit from integrated decontamination strategies to prevent blood and debris from drying on stored instrument tips. In combination with a slight overpressure within the sterile casing, this could further reduce contamination risk during storage. Together, these developments may help advance the ICES from a proof of concept toward a practical and reliable system for automated robotic instrument exchange in clinical practice.

5. Conclusions

The automatic Instrument Carousel Exchange System (ICES) prototype was designed and successfully validated for the AdLap surgical robotic platform with modular instruments. The system enabled reliable autonomous exchange of reusable SATA instrument shafts while maintaining safe and stable operation. Although further optimization of exchange speed and system integration is required, the ICES demonstrates the feasibility of automated modular instrument handling in robotic minimally invasive surgery. Future integration of such systems may contribute to more efficient, sustainable, and increasingly autonomous robotic operating room workflows.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/act15070381/s1. References [28] are cited in the supplementary materials.

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