A Robotic System for Solo Surgery in Flexible Ureterorenoscopy

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***Abstract*—Urolithiasis is a common disease with increasing prevalence across all ages. A common treatment option for smaller kidney stones is flexible ureterorenoscopy (fURS), where a flexible ureteroscope (FU) is used for stone removal and to inspect the renal collecting system. The handling of the flexible ureteroscope and end effectors (EEs), however, is challenging and requires two surgeons. In this article, we introduce a modular robotic system for endoscope manipulation, which enables solo surgery (SSU) and is adaptable to various hand-held FUs. Both the developed hardware components and the proposed workflow and its representation in software are described. We then present and discuss the results of an initial user study. Finally, we describe subsequent developmental steps towards more extensive testing by clinical staff.**

***Index Terms*—Medical robots and systems, physical human-robot interaction, performance evaluation and benchmarking, fURS, DLR MIRO.**

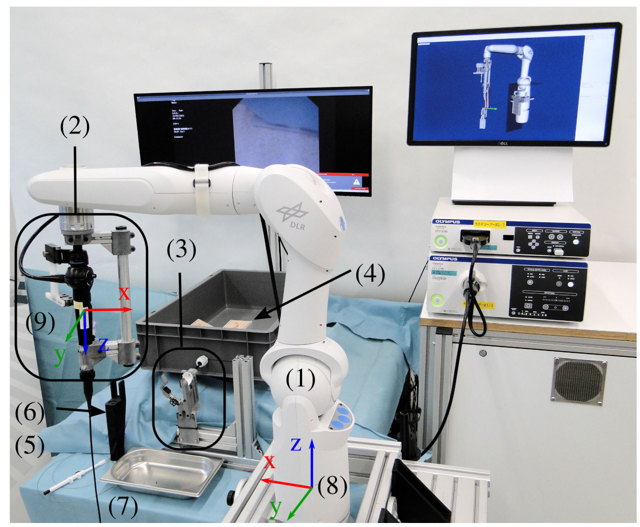

Fig. 1. Setup for the user study: the robot arm DLR MIRO (1), the *Robot-Side Unit* (RSU) (2) attaching the handle of the flexible ureteroscope (FU) to the robot, and the *Patient-Side Unit* (PSU) (3) next to the box with the kidney phantom (4). The extraction basket (5), the registration probe (6) and a stainless steel bowl for the stone fragments (7) are arranged in front of the PSU. The left screen shows the endoscope image, the right screen the representation of the robotic system in virtual reality (VR). The two coordinate systems are MBASE (8) and MTCP (9).

I. Introduction

UROLITHIASIS (stone formation in the urinary tract) occurs worldwide in women and men of all ages [1], and has become more prevalent during the past 100 years [2]. Its lifetime prevalence rates range between 7–13% in North America, 5–9% in Europe and 1–5% in Asia [3]. The overall prevalence in the USA rose from 5.2% in the years 1988-1994 [4] to 8.4% from 2007 to 2010 [5].

The recommended treatment options depend on the stone's size, location and composition [1], [6]–[8]. In the medical expulsive therapy (MET), drugs are administered to support the stone's spontaneous passage by relaxing the ureter [6], or to initiate chemolysis of uric acid stones [7]. This method is mainly applied for smaller stones with diameters under 6 mm [8]. Active stone management methods include the extracorporeal shock wave lithotripsy (ESWL), percutaneous nephrolithotomy (PNL) and ureteroscopy (URS) [7].

In URS, either a rigid or a flexible endoscope, which is usually bendable at one degree of freedom (DoF), is advanced through the patient's urinary tract to the location of the stone. Then the stone is either captured directly, using forceps or a basket, or it is first disintegrated via laser or an ultrasonic/pneumatic system [7]. All these end effectors (EEs) are inserted through the endoscope's working channel. A ureteral access sheath (UAS) simplifies the access to the upper urinary tract especially when the ureteroscope needs to be inserted multiple times [7], [9]. Technical improvements in the design of flexible ureteroscopes (FU, endoscopes for the urinary tract), few contraindications, and this approach's utility throughout the ureter have led to increased use of URS [7], [10], [11].

A. Challenges in Ureteroscopy

The manual handling of ureteroscopes, especially of FUs, is technically demanding and requires two surgeons: the first surgeon holds the flexible endoscope's handle in one hand and

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actuates the rotation of the endoscope around its longitudinal axis by turning the handle and the angulation of the endoscope tip by moving a lever on the handle; with the other hand, he/she controls the flexible endoscope shaft's advance into the patient. The second surgeon operates the EEs.

This current clinical practice in flexible ureteroscopy (fURS) poses different challenges to the surgeons:

- **X-ray exposure**: Fluoroscopic imaging is the standard intraoperative imaging method in URS [6], [7]. Park et al. reported a mean fluoroscopy duration of 5.13 min for a mean surgery duration of 83.2 min [12]. However, this fluoroscopy duration can be reduced significantly by optimized operation techniques and protocols [13]. The surgeon holding the endoscope is located close to the X-ray unit during fluorosocpy and thus must wear a lead vest.
- **Poor ergonomics**: manipulating the endoscope reinforces unergonomic body postures and hand positions necessary for twisting the handle and/or actuating the control elements. In a study with 122 endourologists, 32% of them reported hand or wrist problems [14]. Tjiam et al. interviewed 285 urologists, 177 (62.1%) of whom reported work-related musculoskeletal problems [15].
- **Limited work space**: during fURS, both surgeons have to interact directly with the endoscope and thus position themselves between the patient's spread legs. This obvious lack of space can lead to unergonomic positions and increase in stress for the surgeons.
- **Complex coordination**: when using an EE such as a laser fiber or a basket, the movements of endoscope and tool must be coordinated, which requires good mutual understanding between surgeons.

B. Contribution

To address the described challenges, we propose a robotic system for fURS, which enables a single surgeon to perform this intervention (solo surgery or SSU). The system is mobile, compact, adaptable to various hand-held FUs, requires only minor modifications in the existing clinical workflow and allows quick conversion to manual fURS if necessary. The developed system, the workflow implementation and the results of an initial user study investigating the stone fragment removal without assistant (as one core aspect of SSU) are presented in the following.

II. State of the Art

For the robotic control of flexible endoscopes, two different approaches have been developed: attachable actuation units actuate the endoscope's DoFs while the endoscope handle with the actuation unit is either hand-held or fixated to a passive arm. Robotic telemanipulation systems enable the control of the endoscope from a remote surgeon console.

A. Attachable Actuation Units for Flexible Endoscopes

For endolaryngeal flexible endoscopes, Olds et al. presented a system with five passive DoFs to position the robotic unit and three actuated DoFs for translation, rotation and bending of the endoscope. It can be adapted to various endoscopes and is telemanipulated via a SpaceMouse or a control unit with two joysticks [16] at the operating table (OR table).

Fang et al. developed a hand-held actuation unit for a flexible rhino endoscope. Its two servo motors for the rotation of the endoscope handle and the bending of the endoscope tip are either controlled by the surgeon via two push buttons or by a computer [17].

Zhang et al. proposed an actuation unit with three DoFs for a FU, which enables simple snap-in of the endoscope and the control of the tip motions via joystick [18].

Several attachable actuation units for colonoscopes have been developed. In the system by Ruiter et al., the translation along and the rotation around the shaft axis are actuated manually while an actuation unit at the endoscope handle allows teleoperation of the tip bending via a custom remote control. The endoscope handle with the actuation unit is either held by the surgeon or attached to a docking station [19]. A later version added a module for the teleoperated translation and rotation of the endoscope shaft and replaced the remote control by a commercial haptic device [20].

In the work of Iwasa et al., an actuation unit with three DoFs (rotation and bending in two planes) surrounds the endoscope handle while the translation of the shaft is driven by a movable shaft guide. The system is controlled using a custom-made controller with nearby buttons for suction, air supply and water supply [21].

The *easyEndo* system by Lee et al. provides an actuation of the colonoscope's bending and rotation DoFs and the EE's translation and rotation DoFs via a single custom controller. The endoscope handle with the surrounding actuation unit is attached to two passive positioning arms [22].

B. Robotic Telemanipulation Systems

Desai et al. demonstrated robotic fURS for kidney stones using the modified Sensei robotic catheter system (Hansen Medical, Mountain View, CA, USA) first in an animal model and then in a clinical trial on 18 patients. The tip of a custom-built flexible fiberscope was glued to the tip of the inner catheter sheath to enable telemanipulation. Since the robotic system was originally designed for cardiac applications, the outer catheter's diameter is, at 14 Fr (about 4.7 mm), relatively large. The robot arm has a limited workspace, thus its base has to be repositioned while the ureteroscope is advanced towards the kidney [23].

The *Avicenna Roboflex* (ELMED Medical Systems, Ankara, Turkey) was the first commercially available system for the robotic telemanipulation of FUs. It consists of a cart with a robotic arm for manipulating the FU and a surgeon console. The robotic arm enables height adjustment, translation and rotation of the endoscope handle as well as actuation of the endoscope tip bending. The system can be adapted to different FUs by exchanging adapter plates at the robotic arm. The surgeon console provides a joystick for the translation and rotation of the endoscope, a wheel for bending the endoscope tip, foot pedals for the activation of fluoroscopy and laser, and a touchscreen

TABLE I
PROPERTIES OF ATTACHABLE ACTUATION UNITS (AU), TELEMANIPULATION SYSTEMS (TS) AND THE DEVELOPED SYSTEM (DS) (DEGREES OF PROPERTY FULFILLMENT: + HIGH, ○ MEDIUM, - LOW)

Property	AU	TS	DS
Compactness	+	-	○
Actuation of endoscope DoF	○	+	-
Weight compensation	○	+	+
Easy conversion to manual fURS	○	-	+
Haptic feedback from OR site	-	-	+
Enable solo surgery	○	-	+

for accessing additional functionalities like irrigation [24]. The system was successfully evaluated in clinical trials [25], [26].

Shu et al. and Zhao et al. have recently presented similar telemanipulation systems for fURS. The system by Shu et al. actuates all DoFs of the FU, provides an actuated support for the flexible shaft and an actuation for moving surgical EEs. It is controlled via two commercial haptic devices and monitors the intra-renal pressure [27].

The endoscope manipulator by Zhao et al. provides, besides telemanipulation of the endoscope's DoFs, a passive mechanism for supporting the UAS and an actuation mechanism for surgical EEs. An assistance mechanism with two rubber wheels at the entrance to the UAS guides the shaft of the FU. The system is controlled via two coupled joysticks with three actuated DoFs [28].

C. Properties of the Existing Technical Solutions

As displayed in Table I, the main advantage of attachable actuation units is their compactness, but most of them do not actuate all DoFs of the flexible endoscope. Furthermore, weight compensation is only given when endoscope and actuation unit are attached to the passive arm. The adaptation of the passive arm's pose is cumbersome, since the combined weight of endoscope, actuation unit and passive arm has to be handled while the passive arm restricts the motion capabilities. This complicates SSU in interventions like fURS, which require regular intraoperative repositioning of the endoscope handle.

Telemanipulation systems enable control of the endoscope's (and the EE's) DoFs, and provide full weight compensation. However, the combined footprint of robot cart and surgeon console is large and they do not support SSU, since a second surgeon is needed at the OR table (e.g. to connect the UAS to the system or to change EEs). The intraoperative conversion to manual fURS requires multiple, complex steps (sterile dressing of the surgeon, detachment of endoscope from the robotic system, removal of robot cart from patient).

All described attachable actuation units, and all but one of the described telemanipulation systems, either provide no haptic feedback or can only feed back the actuation torques of the motor. The telemanipulation system by Shu et al. has a torque sensor at the bending DoF of the FU, but no comparable sensors for the other two DoFs. Thus, the surgeon's sense of touch is diminished or lost.

III. MATERIALS AND METHODS

Our system aims to address these shortcomings in the state of the art, by enabling SSU with minimal modifications of the existing clinical workflow. The subsequently described materials and methods were applied to reach this target.

A. Materials

1) DLR Miro: the robotic component of the developed system, the DLR MIRO, is a versatile robot for medical applications [29]. It provides 7 actuated DoFs and a maximum payload of 3 kg. Its compactness and low weight (about 10 kg) simplify its integration into the OR. An integrated user interface with six programmable buttons and eight RGB-LEDs at the tool interface allows physical human-robot interaction (pHRI) [30].

The DLR MIRO is a flexible joint robot with strong joint couplings. Therefore, from a control perspective, a multi-input-multi-output (MIMO) joint controller is applied, comprising full state feedback of the measured drive side joint positions and velocities, as well as link side torques and torque derivatives. An additional friction observer further enhances the control performance [31], [32]. This controller provides three interfaces at joint level:

- **Stop interface *stopIF:*** fixes the robot at the current position. This is the default controller, which can be activated anytime during robot operation.
- **Joint position controller *posIF:*** tracks trajectories in joint space. The *posIF* is used to interpolate towards arbitrary target poses ($ipol_{posIF}$).
- **Joint torque controller *torIF:*** regulates the link sided torques. It enables on one hand gravity compensated, hands-on movement of the robot ($gravComp_{torIF}$). On the other hand, it can be used to set up a Cartesian impedance control $cartImp_{torIF}$ [33].

Switching between two control interfaces is only possible, if the state difference between active and requested interface is within a certain threshold. To guarantee a smooth switching, the initial state difference is gradually faded down until the state of the requested interface is fully applied.

2) Other System Components: A commercially available FU *Olympus URF-V* (Olympus Deutschland GmbH, Hamburg, Germany) was used in the system development. The disposables included a *Flexor Ureteral Access Sheath FUS-120045* and a stone extractor *NGage NGE-017115* (both CookMedical Inc., Bloomington, IN, USA). The silicone model of a left kidney (SAMED GmbH, Dresden, Germany) was used in the user study.

B. Methods

Continuous feedback from surgeons supported the development process of the SSU system for fURS.

1) System Structure: As displayed in Fig. 2, the DLR MIRO robot is mounted on a mobile cart, which can be positioned beside the OR table. The endoscope handle is attached to the *Robot-Side Unit* (RSU) at the tool interface of the MIRO. The portable *Patient-Side Unit* (PSU) is positioned next to the patient at the OR table. It fixates both the flexible shaft of the FU and

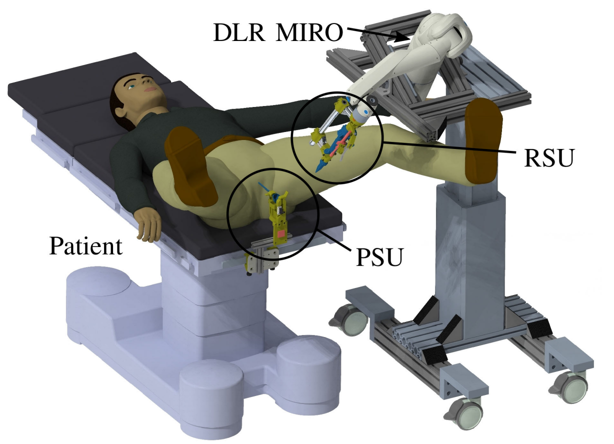

Fig. 2. Operating room setup of the developed system for solo surgery (SSU): The robot arm DLR MIRO with the RSU is attached to a mobile cart. The PSU is positioned between the spread legs of the patient.

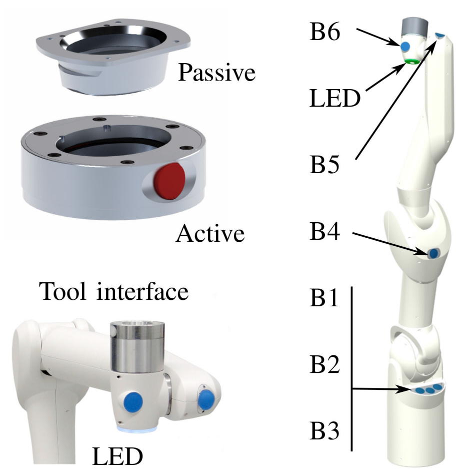

Fig. 3. Positions of the buttons (B1-B6) and the LED ring on the DLR MIRO (Right). Detail views of the developed tool interface (top left) and the MIRO wrist with buttons, LED ring and tool interface (bottom left).

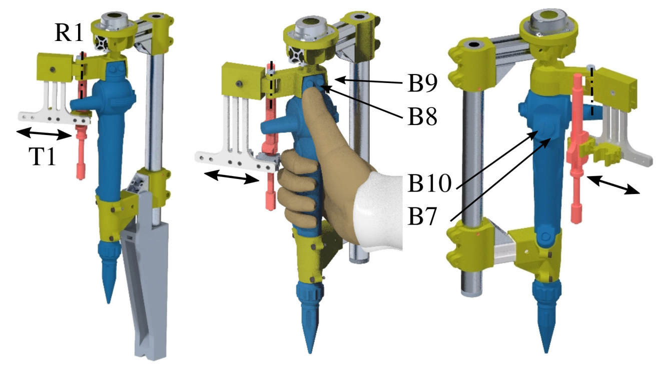

Fig. 4. Detail view of the RSU (endoscope handle in blue, EE in red, rapid prototyping parts in yellow, aluminum parts in silver, POM parts in white, registration probe in grey): Left: The RSU with attached registration probe for the PSU. Middle: RSU with detached registration probe and right hand of the user. Right: Back view of the RSU with the clamps for the EE.

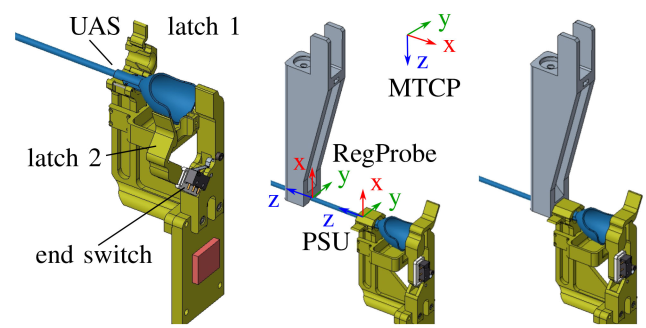

Fig. 5. Detail view of the PSU: Left: the UAS (blue) is clamped to the PSU tool-free by closing latch 1. Latch 2 with the attached end switch can fixate the shaft of the FU. Middle and Right: the registration of the PSU pose using the registration probe at the RSU.

the UAS. In the following, the single components are discussed in greater detail.

2) DLR Miro: Intraoperatively, the DLR MIRO both serves as a gravity-compensated stand for the RSU and as a measurement device for registering the PSU pose. To optimize the workspace usage of the robot, its mobile cart allows height-adjustment and tilting of the robot base.

A custom tool interface (see Fig. 3, top left) enables a tool-free, torsion-proof and self-centering connection of MIRO and RSU. When the RSU-mounted passive docking partner is inserted into the robot-mounted active docking partner, an elastic circular ring in the active docking partner is deformed to an oval until it snaps into the groove of the passive docking partner. To remove the RSU, the two buttons on the active docking partner are pressed. The lightweight and simple geometry of the passive docking partner is well-suited for sterile tools like the RSU. A Hall sensor in the active and a magnet in the passive docking partner enable the detection of tool attachment and removal.

3) Robot-Side Unit (RSU): The RSU, as shown in Fig. 4, holds the FU handle (blue) and the surgical end effectors (red). Its design ensures free access to the lever of the endoscope handle, its buttons and its working channel. Instead of the stone extractor in Fig. 4, other EEs can be fixated to the polyoxymethylene (POM) structure part (white) as well, provided the interface (yellow) between EE and POM structure is adapted accordingly. The POM part can be translated (T1) and rotated (R1) w.r.t. the FU handle to suit different hand sizes and finger lengths of the surgeons.

4) Patient-Side Unit (PSU): The PSU is a low-cost, disposable part, which is positioned close to the patient at the OR table. It provides an interface for tool-free attachment of the UAS, which prevents slipping of the UAS out of the patient and keeps it at a defined position. This mechanical fixture of the UAS is crucial for the registration of the PSU pose w.r.t. to the MIRO base (see section III-B5). This information can be used to, among others, define virtual fixtures (VF), which prevent extensive bending of the endoscope's flexible shaft at the entrance of the UAS.

Furthermore, the PSU has a clamping mechanism to fixate the FU's shaft (see Fig. 5, left). This allows the surgeon to release the FU shaft and have both hands free. An end switch detects

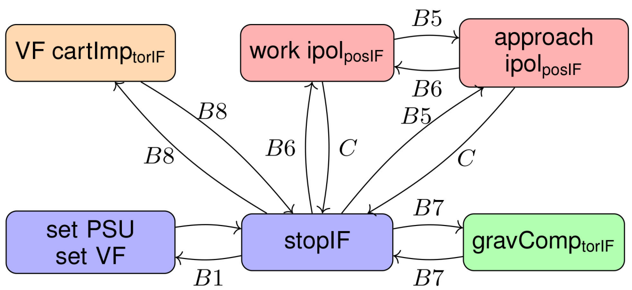

Fig. 6. Workflow for robotic solo surgery: Starting from the default state *stopIF*, different states can be activated via the buttons of the MIRO robot (B1-B6, see Fig. 3) and the FU (B7-B10, see Fig. 4).

the closure of the clamping mechanism and switches the MIRO to *stopIF* (see Fig. 6). This prevents pulling on the flexible shaft, which could damage the endoscope.

5) Registration Procedure: To register the PSU pose w.r.t. the base of the MIRO, a detachable registration probe is connected to the RSU (see Fig. 4, left) using a form closure and a magnet. Its predefined geometry and a prismatic guide for the UAS tube at its lower end allow for the registration of the PSU pose without an additional tracking system:

The robot is guided in *gravComp* mode (see Fig. 6) towards the tube of the UAS. When the prismatic guide touches it on both surfaces and the registration probe is orientated vertically (see Fig. 5 middle), the probe is moved along the UAS until it reaches the PSU (see Fig. 5, right). The geometry of the registration probe (RegProbe) is known, its pose w.r.t. to the MIRO base (MBase) and the MIRO tool center point (MTCP) is described by:

$$^{\text{MBase}}\mathbf{T}_{\text{RegProbe}} = ^{\text{MBase}}\mathbf{T}_{\text{MTCP}}(q) \cdot ^{\text{MTCP}}\mathbf{T}_{\text{RegProbe}} \quad (1)$$

with $^{\text{x}}\mathbf{T}_{\text{y}}$: homogeneous transformation matrix from x to y [34].

When the user confirms the contact between registration probe and PSU by pressing MIRO button B1 (see Fig. 3, right), $^{\text{MBase}}\mathbf{T}_{\text{PSU}}$ is set to $^{\text{MBase}}\mathbf{T}_{\text{RegProbe}}$.

6) Workflow: The workflow is implemented as state machine with the following control states (see Fig. 6):

- **Stop** *stopIF:* used to fix the robot during stone removal. This default state is either triggered by the end switch at the PSU (see Fig. 5, left) or by leaving the current state by pressing button B7 or B8 a second time.
- **Joint space interpolator** $ipol_{posIF}$: used to move the robot to a predefined pose (e.g. approach or work pose). If a collision (C) is detected during the movement, the MIRO immediately returns to *stopIF*. This state was used in the user study for a repeatable definition of the VFs, and a repeatable starting position of the robot (see section III-C).
- **Gravity compensation** $gravComp_{torIF}$: used for the PSU registration. The nullspace of the robot is controlled in a way, which allows single-handed movement of the FU.
- **Virtual fixtures (VF) based on cartesian impedance control** $cartImp_{torIF}$: used during FU operation. The translational motion is limited to a predefined box to avoid extensive bending of the endoscope's flexible shaft and collisions between RSU and PSU. Two rotational DoFs of the MIRO TCP are fixed, such that only the rotation around the endoscope handle axis is allowed to simplify the endoscope handling.

The users triggers the transitions between the states via the buttons of the MIRO (B2-B6, see Fig. 3) and the endoscope (B7-B10, see Fig. 4) or by clicking on the GUI. Button B1 is used to register the PSU (see section III-B5). The GUI and the LED ring of the MIRO display the current state of the workflow, i.e. the enabled controller.

C. Initial User Study

In an initial user study, we compared the manual and the robotic approach for a central step of fURS: removal of kidney stone fragments using an extraction basket.

1) Participants: The ten participants of the study (5 male, 5 female, average age 31.4 ± 7.8 years) rated their experience in using robots, on a scale of 1-10, with 1 = none to 10 = expert, as 6.7 ± 1.7, and their experience in using flexible endoscopes as 1.6 ± 1.0. [1]

2) Task: In the test setup from Fig. 1, the participants had to grasp and remove three stone fragments, which were small enough for UAS passage and had been positioned at predefined sites in the renal pelvis of the kidney model. The UAS was already attached to the PSU and inserted into the kidney model. The renal calyces had been plugged to prevent the stones from falling into them. Each participant had to perform the task in the manual and the robotic scenario. In the manual scenario, the participants took the role of the surgeon and navigated the FU while an assistant opened and closed the extraction basket on their commands. The assistant was of high expertise in robotics but low expertise in fURS, and was the same person for all participants. In the robotic scenario, the participants navigated the FU and also handled the extraction basket. To prevent extensive kinking of the FU shaft, and collisions between the FU handle and the UAS, VFs in form of a rectangular box with the side lengths 150x150x250 mm were defined as follows: the robot was moved in the joint space interpolator to the predefined position *work* $ipol_{\text{posIF}}$ in the center of the workspace. The VFs with their predefined shape and dimensions were set based on the current robot pose. Subsequently, the robot was driven to the predefined position *approach* $ipol_{\text{posIF}}$, from which the participants started the stone extraction.

3) Procedure: Five participants started with the manual and five with the robotic scenario to account for training effects. Before the actual test task, a training was done in each scenario: the removal of one stone fragment was demonstrated to the participants, subsequently they removed two stones themselves.

After the training, the three stone fragments were put to the predefined sites in the kidney model again and the actual test task was started. The time for grasping and removal of each stone fragment was measured and after each scenario the subjective user experience was inquired using the NASA-TLX [35] and the

[1] All participants had signed a declaration of consent before. The obtained data (measured times, robot data, entries to NASA-TLX and SUS) were made anonymous immediately after the end of the user study.

TABLE II
RESULTS OF THE USER STUDY WITH N=10 PARTICIPANTS

	Manual scenario	Robotic scenario
Removed stones	29 / 30	28 / 30
Duration test task [s]	156.8 ± 78.7	185.7 ± 68.2
NASA-TLX	42.7 ± 19.4	42.7 ± 16.6
SUS value	63.5 ± 18.6	71.3 ± 17.6

System Usability Scale (SUS) [36], [37]. Additionally, relevant robot data were logged in the robotic scenario to quantify the RSU motions in the workspace, the manipulation forces and torques of the user and the forces created by the VFs (see section III-B6).

IV. RESULTS

As displayed in Table II, the participants successfully removed 29 of 30 stones in the manual and 28 of 30 stones in the robotic scenario (each of the ten participants had to remove three stones in each scenario). The three missing stones were successfully grasped, but dropped from the basket when entering the UAS. The completion of the test task took them on average 156.8 ± 78.7 s for the manual scenario and 185.7 ± 68.2 s for the robotic scenario. For the manual scenario, the average workload according to NASA-TLX was 42.7 ± 19.4 and the average SUS value was 63.5 ± 18.6. For the robotic scenario, the average NASA-TLX value was 42.7 ± 16.6 and the average SUS value was 71.3 ± 17.6.

V. DISCUSSION

The developed system uses a FU and EEs for manual fURS. This minimizes the investment for the hospital, allows surgeons to use familiar devices and supports seamless conversion to manual fURS if necessary.

The robot arm DLR MIRO enables pHRI, gravity-compensated positioning of the FU handle and a compact, mobile system. Commercially available cobots could replace the MIRO, if they provide a sufficient workspace and an adequate user interface for pHRI.

As RSU and PSU consist of RP parts, they can be produced as disposables to fulfill sterility requirements. Thanks to the modular design, the RSU can easily be fitted to another FU or EE. Similarly, the PSU can be adapted to another UAS.

In the following, we will discuss the properties of the system w.r.t. Table I, how it addresses the challenges in ureteroscopy, and give an outlook on its future development.

A. Properties of the Developed System

The robotic system has the following properties:

- **Compactness**: the system setup as displayed in Fig. 2 is larger than existing actuation units but smaller than teleoperation systems with additional surgeon console.
- **Actuation of endoscope DoF**: the surgeon actuates all DoF of the endoscope manually. At the same time, VFs at the endoscope handle as applied in the user study can prevent damage to the system and support less experienced users in the endoscope handling. Fig. 7 depicts the trajectories of the MTCP origin during the robotic scenario and the VFs limiting the workspace. The participants rarely reached the VFs (on average only during 4.3 ± 4.5% of the test task duration). Therefore, the VFs, which were defined to protect the system from damage, did not impede the participants significantly in their motions. The norms of the torques about the x- and y- axes of the MTCP, which were created by the VF to allow only rotation around the longitudinal axis of the endoscope handle, were on average 0.31 ± 0.17 Nm. This relatively low value leads to the conclusion that the VF did not cause significant discomfort for the participants.

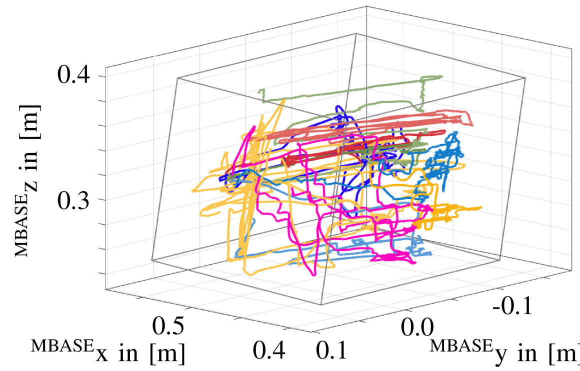

Fig. 7. Trajectories of the origin of the coordinate system MTCP for the participants of the user study in the robotic scenario. The edge lines in the shape of a rectangular box visualize the workspace limits from the VFs.

- **Weight compensation**: to verify the weight compensation and low manipulation forces of the system, the forces and torques applied by the user study participants on the FU handle were calculated. The average force aligned with the gravity vector was -0.165 ± 0.65 N. The low mean value indicates a good gravity compensation of the MIRO. The higher standard deviation is presumably caused by the the robot's inertia and frictional losses in the robot joints, which the participants had to overcome to move the robot. However, the FU handle weighs about 320 g, which corresponds to a force in gravity direction of 3.1 N. Thus, the average load in z-direction is significantly smaller in the robotic scenario. Even the accumulated average user forces in the robotic scenario in x-, y- and z-direction were with 1.51 ± 0.755 N smaller than the weight of the endoscope handle.
- **Easy conversion to manual fURS**: the surgeon has full manual control of all DoFs of the FU when using the developed system. Thus, conversion to manual fURS is rarely required. If it is nonetheless advantageous in an operation step, the surgeon — who is directly at the patient and thus sterile — can simply detach the RSU from the robot using the tool interface in Fig. 3.
- **Haptic feedback from OR site**: due to the manual actuation of all endoscope DoFs, the surgeon receives unaltered haptic feedback from the OR site at his fingertips. The VFs from the robotic system add forces/torques at the FU

handle. Those do not interfere with the haptic information from the OR site as they are felt by the surgeon with the palm of his hand.

- **Solo surgery**: In the user study, the large majority of the stone fragments was successfully removed in both scenarios. Due to the minimum experience of the participants with flexible endoscopes, the stone fragments had been positioned at well accessible spots in renal pelvis. The selection of engineers as study participants was motivated by the focus of this initial user study: verify the technical feasibility and identify possible technical shortcomings of the robotic system. A second user study with focus on system handling and clinical workflow and surgeons as participants is currently under preparation. The average completion time for the test task was about 20% longer in the robotic than in the manual scenario (185.7 s vs. 158.6 s). This difference was statistically non-significant (Wilcoxon signed rank test, significance level 0.05). The reasons for the time increase need further investigation. One factor could be the simultaneous handling of the FU and the EE during the stone grasping. Nonetheless, the result is promising for future developments: compared to the manual approach, the developed robotic approach saves one surgeon and thereby reduces the required surgeon working time from two to 1.2 times the stone extraction time. The subjective workloads as measured by the NASA-TLX match closely for both scenarios. The usability of the robotic scenario according to the SUS value was better and according to [37] corresponds to the adjective rating "good". Overall, the user study confirmed the feasibility of the developed robotic system for stone removal without assistant.

B. Response to Challenges in Ureteroscopy

The system supports the surgeon with the challenges described in section I-A:

- **X-ray exposure**: the surgeon can fixate the FU by clamping its shaft in the PSU and switching the MIRO to *stopIF*. Thus he can leave the area of X-ray exposure when no ureteroscope motion is required during fluoroscopy. In combination with operation techniques for low fluoroscopy usage (compare [13]) this might even allow to avoid X-Ray exposure completely.
- **Poor ergonomics**: ergonomics was not the focus of the user study, but it contributed to the workload ratings of the NASA-TLX. Those were comparable for manual and robotic scenario. Presumably, SSU will allow the surgeon more ergonomic body postures as he/she can choose their position w.r.t. the patient more freely. Since SSU brings additional tasks for the surgeon's hand, the position of the EE attachment w.r.t. the FU handle is crucial for the ergonomics of the hand posture. Thus, the RSU provides configuration options to account for different hand sizes (R1 and T1 in Fig. 4).
- **Limited work space**: this challenge will be significantly diminished by SSU, as the surgeon must share his workspace only with the robotic arm.
- **Complex coordination**: with the developed system, the surgeon can control both FU and EEs. Thus no coordination with a second surgeon is necessary.

C. Outlook

The next development step of the system is the preparation of a user study with surgeons, to investigate the system handling and the compatibility with the medical workflow.

Firstly, the usability and safety of the system shall be improved: while in the current prototype some setup steps still require the use of tools, they shall be possible tool-free in the next redesign. To enable a more flexible positioning of the PSU, a passive holding arm with five DoFs will be inserted between the PSU and the OR table. The described registration of the UAS pose w.r.t. MIRO base is a simple, low-cost, yet effective approach. The current design of the registration probe allows its rotation around the UAS axis. This can influence the pose of VFs, which are defined w.r.t. the UAS pose. As the user can easily verify the vertical orientation of the registration probe, no problems due to wrong registration were observed so far. Nonetheless, the registration probe design will be adapted to prevent undesired rotation around the UAS axis. The backdriveability of the RSU currently depends on the motion direction. Methods to ensure that the inertia and friction felt by the user are low and independent from the motion direction (as e.g. described in [38]), could further enhance the user experience.

Secondly, the functionality of the system shall be extended, so that larger parts of the clinical workflow can be evaluated. This includes the implementation of a sterility concept for the MIRO and the PSU attachment. To enable the disintegration of stones, a laser fiber must be attached to the EE holder and guided to the laser source. Means for irrigation must be integrated to ensure clear vision during stone fragmentation and natural expulsion of small particles.

Finally, the system's capabilities for time-synchronized logging of data from different sources (e.g. endoscope images and robot data) shall be extended to make full use of the valuable information from the planned user study. The logged data will form the base for data mining approaches, which provide us with well-founded, quantitative information about the required workspace, applied forces and user performance in different procedure steps.

VI. Conclusion

We introduced a robotic system for the manipulation of flexible ureteroscopes consisting of a versatile robotic arm on a mobile cart, a *Robot-Side Unit* for the attachment of the endoscope handle and a *Patient-Side Unit* for fixating the ureteral access sheath. The system is compatible with the existing clinical workflow, allows gravity-compensated positioning of the endoscope while preserving the haptic feedback for the surgeon and is a significant step towards solo surgery in fURS. An initial user study confirmed the feasibility of the developed approach for the removal of small stone fragments under laboratory conditions.

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