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Joystick Control with Capacitive Release Switch for a Microsurgical Telemanipulator

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Abstract. **In this article, a new joystick console with release switches based on capacitive sensors is presented. The system is intended to be used in microsurgical procedures, where the surgeon controls a telemanipulator system at the operating-room table, as was done with the Micro Manipulator System (MMS-II) for middle ear surgery. The release switches integrated in the hand rests and in the joysticks prevent unwanted movements of the telemanipulator, even if the joysticks are hit by the surgeon. With a practicable sterilization concept, a small size, and an intuitive handling, the system is well suited for use in standard surgical procedures in close proximity to the surgeon.**

Keywords**: capacitive sensor, joystick control, micro-surgery, middle ear surgery, telemanipulator**

I. INTRODUCTION

Microsurgical interventions at the middle ear are dominated by the small size of the structures that are operated on, such as the malleus, the incus, and the stapes. Hence, the interventions are done with the aid of an operating microscope and special microinstruments, which are moved manually. The stapedotomy, for example, is an intervention where the stapes is partly removed, a small hole (Ø 0.4 mm) is pierced into the stapes footplate, and a tiny prosthesis (Piston) is inserted. Under optimal conditions, the human hand reaches a precision of about 0.1 mm [1]. However, the hand's performance is limited by different factors during a middle ear intervention. This includes, for example, limited access to the operational field, adverse hand posture, unsuitable leverage (e.g., large distance between the region of interest and the surgeon's hand), high manipulating forces, instrument weight, [1] and a limited view of the region of interest [2]. Some of the options to compensate for these deficiencies are as follows: a) uninvolved tissue has to be removed; b) optimal trajectory has to be abandoned; and c) complete visual control has to be given up.

Under such difficult ergonomic conditions, the requirements for surgeon's dexterity are especially stringent [3]. Several research approaches assume that mechatronic systems have the ability to improve the current gold standard in microsurgery concerning precision or spatial limitations [3][4]. Robotic systems are discussed in this manner as a possible remedy.

The Micro Manipulator System II (MMS-II) was developed in our group for providing the surgeon with a teleoperated instrument to overcome the mentioned limitations. The usual dexterity of the surgeon should be assured even under adverse conditions. The manipulator consists of an XY-table with a thin vertical Z-axis, a mechanical articulated arm, and an axis for opening and closing an attached forceps. The manipulator can be easily controlled via PWM signals.

TABLE 1
MMS-II CHARACTERISTICS

XYZ motion	mm	20
Incremental motion Z	mm	0.029
Incremental motion XY	mm	0.044
Forceps motion θ	degrees	15°
Maximal force XY	N	4
Maximal force Z	N	3
Maximal torque forceps	cNm	20
Top speed XYZ	mm/s	40
Scaling factor	-	1:3.5
Length	mm	200
Base diameter	mm	80
Mass manipulator	kg	1

Easy integration into existing surgical workflows of the middle ear surgery is an important aim of the MMS-II system. This implies a sterilization concept, a workflow that has been evaluated within the hospital, an easy user interface, and the possibility of quick change between manual and teleoperated instrument guidance. Thus, the user interface has to be in close proximity to the sterile

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surgeon; in consequence of this, a new input device for that purpose had to be developed. In [4] we have presented the manipulator and the overall concept of the system. An overview of the characteristics is given in table 1. This article is focused on the development of the input device.

A. *Current Surgical Setup in Middle Ear Surgery*

Fig. 1 shows a typical surgical setup for middle ear surgery. The surgeon (Dr. Strauss, Leipzig) (2) sits in front of the patient's (1) head, using a special chair with elbow rest and a microscope (3). On the other side of the operating-room table (OR table), a surgical nurse (4) and the anaesthetist (5) are sitting.

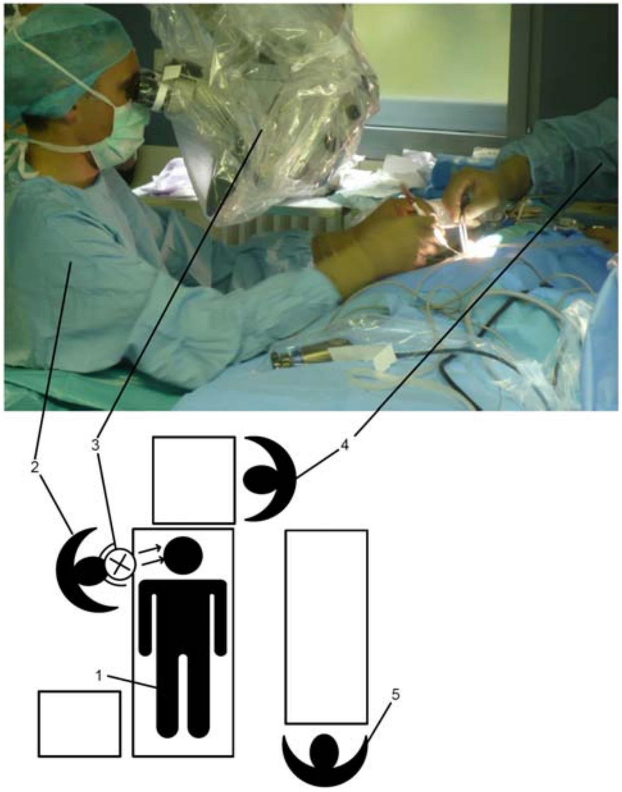


Fig. 1. A surgical setup in middle ear surgery.

B. *Definition of the Requirements*

To define the requirements, we took part in several middle ear interventions. They were recorded on video and subsequently analyzed. The following main requirements and peculiarities were registered:

1) The console has to be in close proximity to the surgeon– ideally in front of the surgeon.
2) The available space for a control at the OR table is very limited. No huge master manipulator arms can be placed. The path to the patient may not be narrowed for the surgeon.
3) The console must be sterile, because the sterile surgeon is handling the console on his own.
4) It cannot be excluded that fluids can flow over the console – e.g., blood and water.
5) Console handling should be intuitive. It should allow a secure control of the manipulator without the need of extensive training.
6) There is the risk that the surgeon could inadvertently hit the joysticks, especially while he/she is operating by hand. Therefore, a mechanism is necessary to prevent unwanted movements of the manipulator.
7) Setup time must be reduced to a minimum. A typical intervention takes one hour. Hence, setup time may not exceed five minutes for the whole manipulator system.
8) Since the MMS-II system is merely an assisting tool that is used in special cases during the operation, a reasonable price for the control must be reached.

C. *State of the Art*

Operational concepts for systems used in microsurgical interventions (e.g., in eye or ear surgery) can be divided into four groups [5]: *Automatic robotic systems* execute a predefined task based on preoperative images, such as MRI or CT. Sensor information can be considered during the task. *Interactive Robots* have a control that is mounted directly on the robot. The sensor can be, for example, a force-torque sensor or a joystick. The robot and the surgeon guide the instrument together. The degrees of freedom of the movements as well as the mechanical impedance (admittanz) can be adapted by the robot, if a force-torque sensor is used. An example is the steady-hand-eye robot [6]. *Micro machines* are dedicated to special tasks such as tremor compensation. They can be handheld or used as tools for other robots, but they are machines rather than robots. An example is the Micron system [7]. *Teleoperated systems* are remote-controlled by the surgeon via master manipulators or joysticks. Thus, visual feedback is needed. Examples are the DaVinci [8] or the RAMS system [9].

For our medical appliance, we have considered only the interactive robot control or teleoperated control. Interactive robots are intuitive to control even in six degrees of freedom; the required force-torque sensors are, however, relatively expensive. Master manipulators provide a direct position control of the slave manipulator – in other words, a pose of the master is related to one or more poses of the slave manipulator. They are often very complex, bulky, and expensive; accordingly, this concept does not fit our setup. Standard joysticks are simple and intuitive, as long as there are not too many degrees of freedom to control. Especially for Cartesian movements, the joystick is a very common and efficient device. If the joysticks provide an efficient range of motion, direct position control is also possible.

Our system has only three degrees of freedom in the X-Y-Z directions and an additional one to open and close the forceps. In our point of view, two joysticks, each with 2 DoF, provide the necessary functionality.

All of the mentioned operational concepts need a mechanism to prevent an unwanted motion of the robot or telemanipulator. Very often this is done by means of release switches. Some concepts for release switches are the following:

Mechanical release switches are used for dead man's switches as a handheld button. Also, foot pedals as release switches are widespread in the clinical routine, since the floor and the surgeon’s feet do not need to be sterile. There are also a couple of OEM joysticks with built-in release switches in the grip. *Light barriers* are usually more comfortable, as they do not require any effort by the user. They react, for example, to the placement of the operator’s head in front of the stereoscope (DaVinci Manipulator [8]). *Proximity Sensors,* also, have proved to be adequate as release switches in safety-related areas. TU Graz, for example, has extended a motor saw with safety features based on capacitive sensors [10].

Problems that occur with these devices are as follows: Foot pedals usually come with cables on the floor and need additional attention from the surgeon; hands are not free when using manual release switches similar to dead man’s controls; sterilization foil causes problems when safety light barriers are used; OEM Joysticks with release switches are too bulky for our purpose.

We propose a small-dimension joystick console optimized for OR needs. An ergonomic housing with hand rests should allow a comfortable and precise movement of the joysticks without fatigue. The integration of capacitive sensors in hand rests and joysticks should provide an automatic and safe release if the surgeon wants to control the manipulator. This release switch must not be disturbed by fluids or by a sterile foil covering the console. The use of standard components and a modular body should ensure reasonable costs. The operation principle, measurement technique, system design, and test results are described in the next section.

II. SYSTEM DESCRIPTION

The controller consists of two industrial joysticks, an ergonomic housing with hand rest, a microcontroller, and two medical power supplies. The joysticks (Megatron, Germany) have an electrical rotation angle of 50° at ±1% linearity and have been chosen for their robustness and compactness. A microcontroller (ATMega 2560, 8Bit, 16 MHz, Atmel, USA) was used as a central control unit. No additional computers are needed to control the manipulator. The microcontroller and the motors of the manipulator are supplied with two external medical power supplies (MPU50, SINPRO, Taiwan). The joysticks and the microcontroller are built inside an aluminum box for purposes of shielding. This box is covered with a plastic housing, which includes ergonomic hand rests (Fig. 3). A switch located on top of the controller allows the system to be shut down manually. Also, capacitive sensors have been integrated in hand rests and in the joystick grips. The manipulator will move only if the sensor in one hand rest and the sensor in the corresponding joystick are released. We have also provided the console with an RS232/RS422 and ISP interface for communication and programming purposes. The main characteristics of the joystick control are given in Table 2.

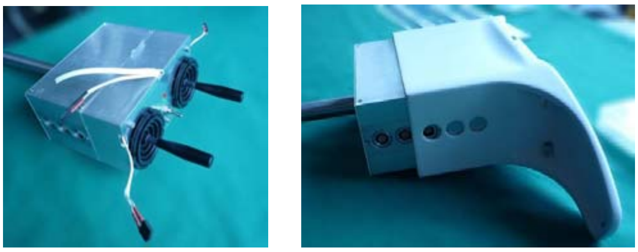


Fig. 3. Metal box with joysticks and plastic cover with capacitive release switches in hand rests.

TABLE 2
CHARACTERISTICS OF THE JOYSTICK CONTROL

Maximum translation at joystick tip (circular arc)	mm	70
Degrees of Freedom	-	4
Mass	kg	1,5
Width	mm	400
Depth	mm	100
Height (without rod)	mm	250
Interfaces	-	RS232/ RS422 ISP
Output to Manipulator	-	PWM 50Hz

A. *Microcontroller Processing*

The Atmel microcontroller reads in the current joystick voltages via four 10-bit ADCs, calculates the moving average (with the last four values) to improve accuracy, and proportionally calculates the motor positions. Each joystick axis thereby relates directly to one degree of freedom of the manipulator. Thus, the computation is very simple. The switch and the capacitive sensors are checked with 100 Hz. The motors are controlled by pulse-width modulation (PWM). Their position is refreshed with 50 Hz. The joysticks’ range of motion at the surgeon’s fingers and the range of motion of the manipulator axes result in a motion downscaling of currently 1 to 3.5. Movement of 7 mm at the joysticks results in a 2-mm movement of the manipulator. An on-chip brownout detection (BOD) circuit controls the microcontroller’s power supply and resets it in case of too low voltage. As a result of that, the program sequence is permanently stopped. To prevent system hang-up in case of runaway code, a watchdog is activated. The watchdog has a separate, 128-kHz oscillator and must be updated every 32 milliseconds – otherwise the microcontroller is also reset (Fig. 4).

Each joystick position is related to exactly one motor position. If the joysticks are moved while the motors are switched off, for safety reasons the motors must not move to the new position when the motors are switched on again. To prevent unexpected movements, the motor is moved only if the joystick position and the motor position are matched. Otherwise the surgeon has to move the joysticks to the position where the manipulator is located. There, the axes again click into place. This does not usually occur and has not yet been considered a problem.

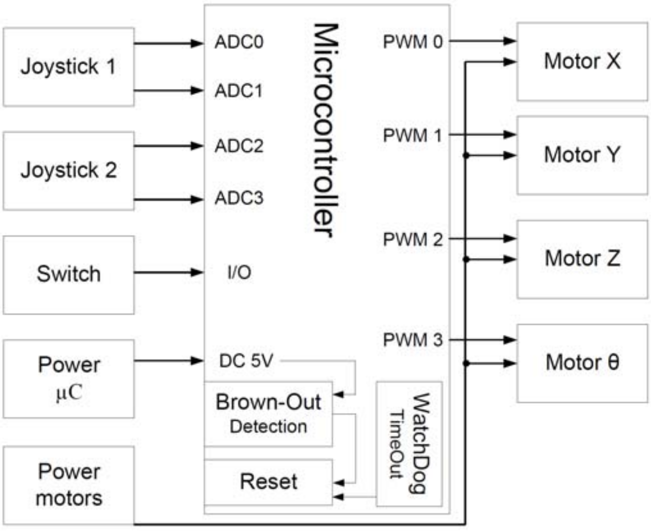


Fig. 4. Control Block Diagram

B. Mechanical and Capacitive Release Switch

A mechanical release switch seemed the most attractive concept at first, since it did not involve electronics. We built a prototype of this concept using silicone keys (Silcos, Germany). A single key as a release switch was not sufficient: the control had to be able to decide whether the key had been accidentally touched or not. Thus, we provided it with several independent keys – and at least two or more keys had to be pressed simultaneously by the operators' palm to activate the control (Fig. 5). This solution did not work very well: pressing several keys at once (as opposed to a single one) involved a substantial amount of force from the operator. As we reduced the necessary force, faulty activations were accumulated if the sterile foil was pulled.

Fig. 5. Mechanical-release switch in the hand rest.

In a next step, we tested the applicability of capacitive sensors. There are various sensor ICs, and a C library that could turn our microcontroller into a sensor. Since we could not afford losing too much computing power, we went for the hardware ICs.

Atmel sensors have the advantage of communicating their state through a simple on/off signal, which makes it possible to use them just like normal mechanical switches. Most companies also provide their sensors with communication interfaces based on I2C, SPI or CAN.

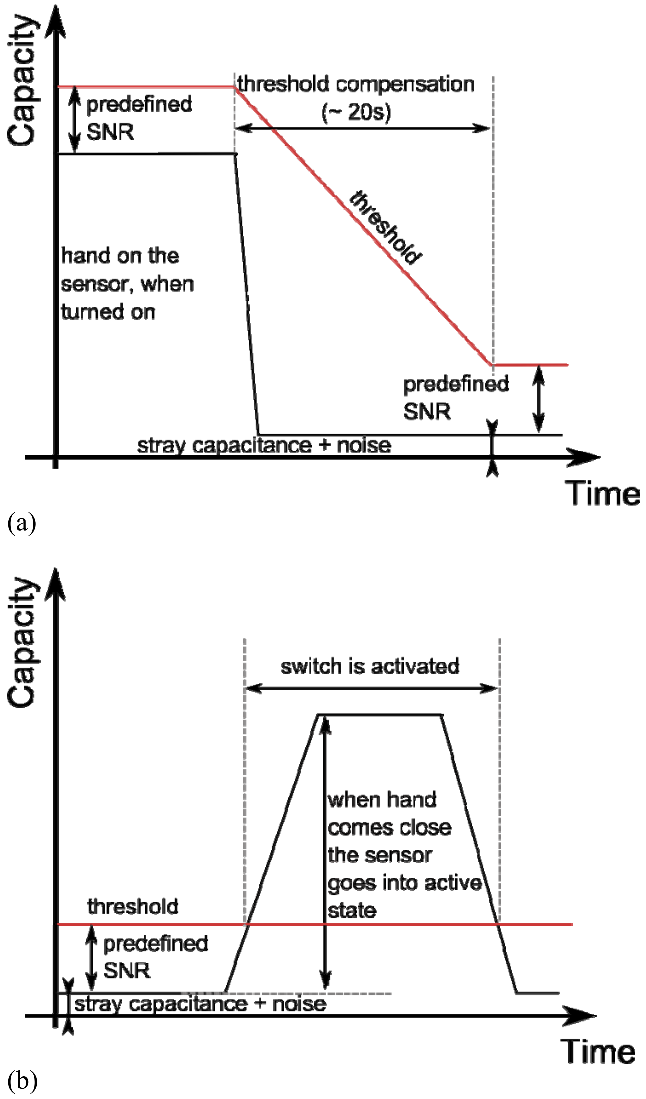
But the most important feature for our application was the adjustable threshold compensation. Capacitive sensors are calibrated every time they are switched on. Hence, both stray capacitance and noise are considered. The sensor's threshold gets adjusted based on a defined signal-to-noise ratio (SNR) and on its stray capacitance. If the surgeon's hand is near the sensor when turning it on, the sensor will no longer detect the hand as a valid threshold. Thus, the surgeon would not be able to activate the manipulator. Hence, it is necessary to compensate for the threshold if the stray capacitance is decreasing (Fig. 6a).

In the other direction, if the stray capacitance is increasing, threshold compensation is unwanted. If the surgeon works with the console for any length of time, the threshold may not be adapted to the new capacity (Fig. 6b). Otherwise the manipulator will stop after a while, during the intervention. In any case, the sensor is not allowed to release the manipulator on its own. Due to some additional functionality, the sensor Qt220a (Atmel) fulfills all of these requirements. The threshold compensation of Fig. 6a takes about 20 seconds to accommodate, when the hand has been removed from the console. This was enough for our purpose, since the console is energized about five minutes before the intervention.

C. Implementation of the Capacitive Release Switches

We have integrated four sensor areas into the joystick control: two are located in the hand rest, and two in the joystick knobs. Each of the sensor areas is connected with an Atmel Qt220 proximity sensor chip (Fig. 7). The Proximity Sensor built into the hand rest consists of a double-sided PCB board (35µm copper) with the sensor area on one side and the QT220 chip on the other side (Fig. 8). This flat sensor area has a strong preference to detect objects only in its normal direction. This prevents accidental release of the manipulator by the surgeon's touching the control with his body. We also tested a version with two sensors on each side, where each sensor area was divided in two meander-shaped parts. But self-interference and differences in stray capacities made it difficult to calibrate the two channels.

The realized two sensors in the hand rests are not sufficient. Safety requires that at least two sensors must be released to activate the manipulator. The surgeon should be able to operate simultaneously by hand and with the manipulator; hence, the ability to operate the console by a single hand became a requirement. Thus, we decided to use the joystick knobs also as a sensor area. A metal pin inside each knob was connected by wire to a sensor IC. This solution worked well – but even with the thinnest silicone cables, a small mechanical resistance could be felt when moving the joystick in a very precise way. A remedy was found through connecting the joystick knob with the sensor IC by two ball plungers made of stainless steel.



(a)

(b)

Fig. 6. Threshold compensation of the Qt220a. The two diagrams depict the slow threshold compensation mechanism (a) downwards. The threshold compensation does not occur upwards, as intended (b).

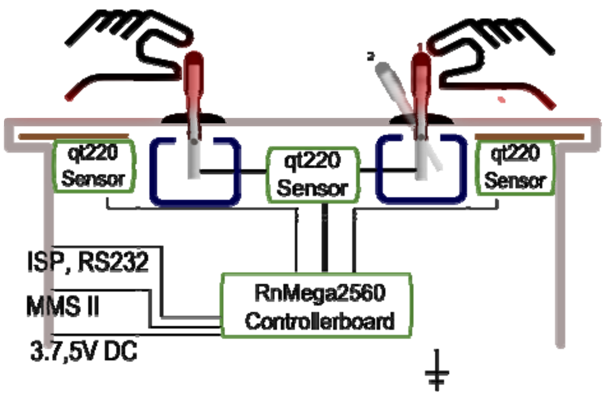


Fig. 7. System configuration of the Joystick Console with capacitive release switches.

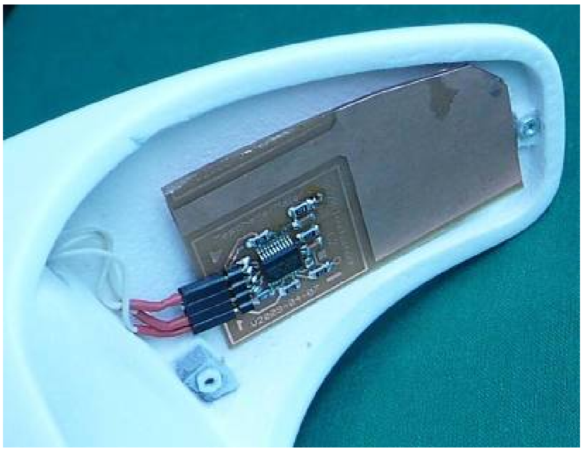


Fig. 8. Capacitive sensor IC together with sensor area in the hand rest.

III. INTEGRATION IN OPERATIONAL PROCEDURES

The first step in using the MMS-II consists in mounting the controller and the manipulator on the side rail of the standard OR table. The manipulator is mounted next to the surgeon’s right or left hand. The joystick controller is attached directly in front of the surgeon. Both components are then covered with sterile foils. The surgeon exposes the middle ear as usual (with access through the temporal bone behind the ear or through the external auditory channel). To access a teleoperated instrument, the surgeon clips the required instrument onto the manipulator’s holders and aligns the manipulator with the operating field, using the articulated arm. The manipulator is ready for use and can be controlled with the joysticks immediately upon being switched on. As soon as the surgeon touches one joystick and one hand rest, the manipulator is released automatically (Fig. 9). The manipulator’s small size enables it to work manually and to be teleoperated in parallel – for example, if a third hand is needed. At anytime the manipulator can be swung in or out, as needed, during the intervention.

Fig. 9. Placement of the MMS-II at the side rail of the OR table.

IV. EXPERIMENTS

The primary goal of the following experiment was to show that the release switches based on capacitor sensors do not negatively affect the handling of the manipulator.

Especially we wanted to show that no faulty activation of the manipulator would occur, even if fluids were spilled over the console.

A. *Experiment Design*

Our experimental design presented in this section is oriented onto the surgical setup shown in chapter I-A. We developed a model that simulates an intervention in the middle ear. Twenty-five 0.5-mm holes were drilled in a plate coated with copper. Every hole was surrounded by an isolation ring with a one-millimeter diameter. Behind the perforated plate, a metal plate was fastened (Fig. 10). The participants in the test were required to hit inside the holes with a pointed instrument, using the manipulator. The instrument is used, for example, to pierce the footplate of the stapes in stapes surgery. The tip was 0.4 mm in diameter. The non-isolated part of the perforated plate and the plate arranged behind it were connected to a microcontroller, which puts a high-impedance voltage of 5 V onto the plates. The instrument was connected to the ground of the microcontroller. As soon as the instrument touched one of the plates, the microcontroller would detect the voltage fall. An attempt was considered successful if the participants touched the ground of the hole. In that case, a positive signal was sounded. If they touched the perforated plate, a negative signal was sounded. The sampling rate was set to 50 Hz. Between every attempt to hit the holes, the participants were instructed to put their hands on the OR table in front of them while reaching over the console, in order to simulate a surgeon's movement while working on a patient. The manipulator and the joystick control were mounted at a standard OR table. The manipulator and the console were covered with sterile foils. The instrument was clipped onto the manipulator's instrument holder and roughly aligned to the model by using the articulated arm. Prior to the experiment, every participant had been introduced to the system and had received five minutes of training. There was no time limit for the task. Participants were told to perform the task as precisely as possible, avoiding any mistakes. During the experiment, the console and the model were connected to a computer using RS232. The transmitted strings consisted of the state for every proximity sensor and the state of the model (i.e., successful hit or unwanted contact). The computer registered the incoming signal together with a time stamp.

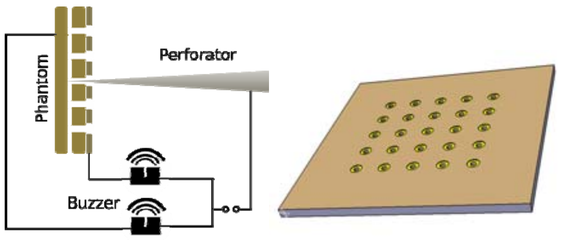


Fig 10. Model with perforated plate to evaluate the joystick control.

One of our concerns was how the release switch would deal with liquids that were spilled over the sterilization foil. Atmel claims that the QT220 has a mechanism to recognize water films. So we did not expect a response from the release switch. We spilled 0.5 liter of water over the console. The release switch showed no response, and the proximity sensors worked as expected, even through the water film.

B. *Results*

In order to evaluate the recorded data, we plotted them on a timeline, such as in Fig. 11a. Every activitation should be clearly identified either as a participant actually using the controller or as an accidental release. Figure 11b shows an example of an unwanted contact (error, red line at second 45). But since the contact did not occur when the participant reached over the console (white space), it most likely happened due to an operator error, and it was not related to the safety switch. Thus no critical error had occurred. Occasionally, it took a while to release the safety switch completely to activate the controller. That happened if the participants moved their hands after touching the hand rest, looking for a comfortable position (Fig. 11c). The evaluation of the entire dataset showed that the release switches do fulfill the mentioned requirements. No faulty activations of the manipulator have occurred. An overview of the data is shown in Table 3.

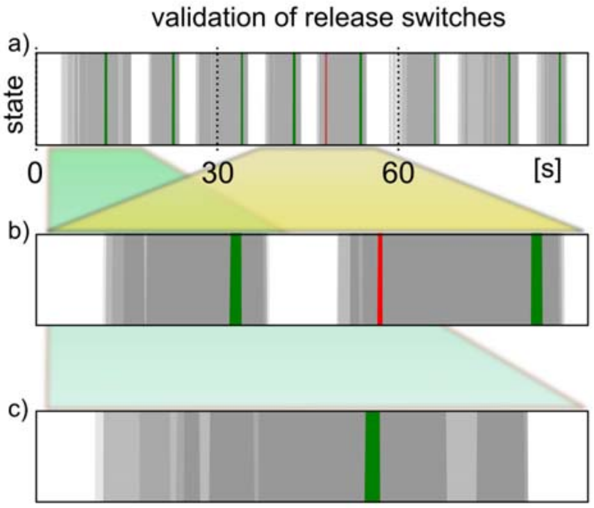


Fig. 11a-c. Timeline of the experiment: Red lines denote unwanted contact with the model's top surface (second 45); green represents a successful attempt at hitting a hole in the model (e.g., second 50). The various shades of gray correspond to the number of individual proximity sensors being activated simultaneously. Only two of the sensors have to be activated (hand rest and joystick) to release the manipulator.

TABLE 3: EXPERIMENT RESULTS.

Participant	*Errors*	*Critical Errors*	*Number of attempts*	*Duration*
1	0	0	25	4:40
2	1	0	20	3:25
3	0	0	25	2.45
4	2	0	25	2:30
5	5	0	25	3:50

V. CONCLUSION

In this article, a new joystick control for the Micro

Manipulator System (MMS-II) has been presented. The goal was to develop a joystick control that could be integrated in existing surgical procedures. The console can be installed in close proximity to the surgeon, due to an capacitive release switch, which is integrated into the hand rests and into the joystick knobs. The joystick control uses a microcontroller for all functionality, whereas no additional computers are needed to control the manipulator. The described system is small, lightweight, and inexpensive to reproduce, and it has a practicable sterilization concept. Currently, we are working on an active control with motorized joysticks.

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