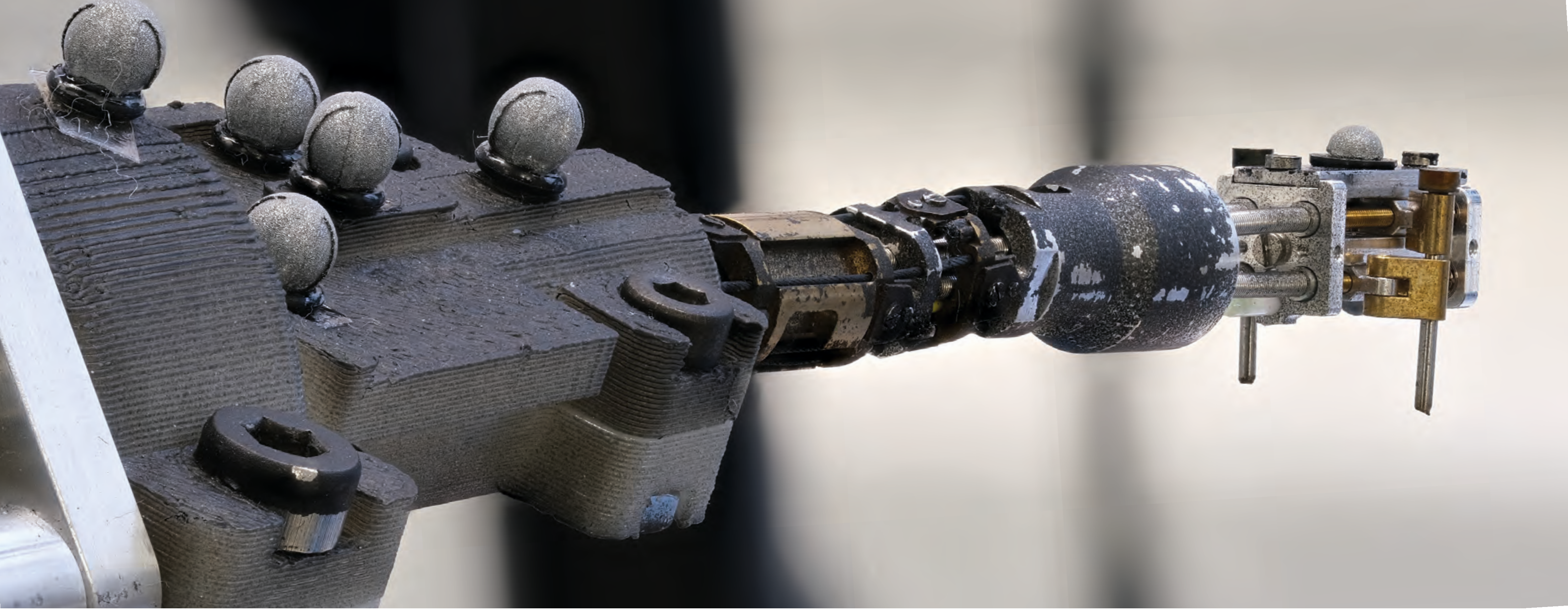
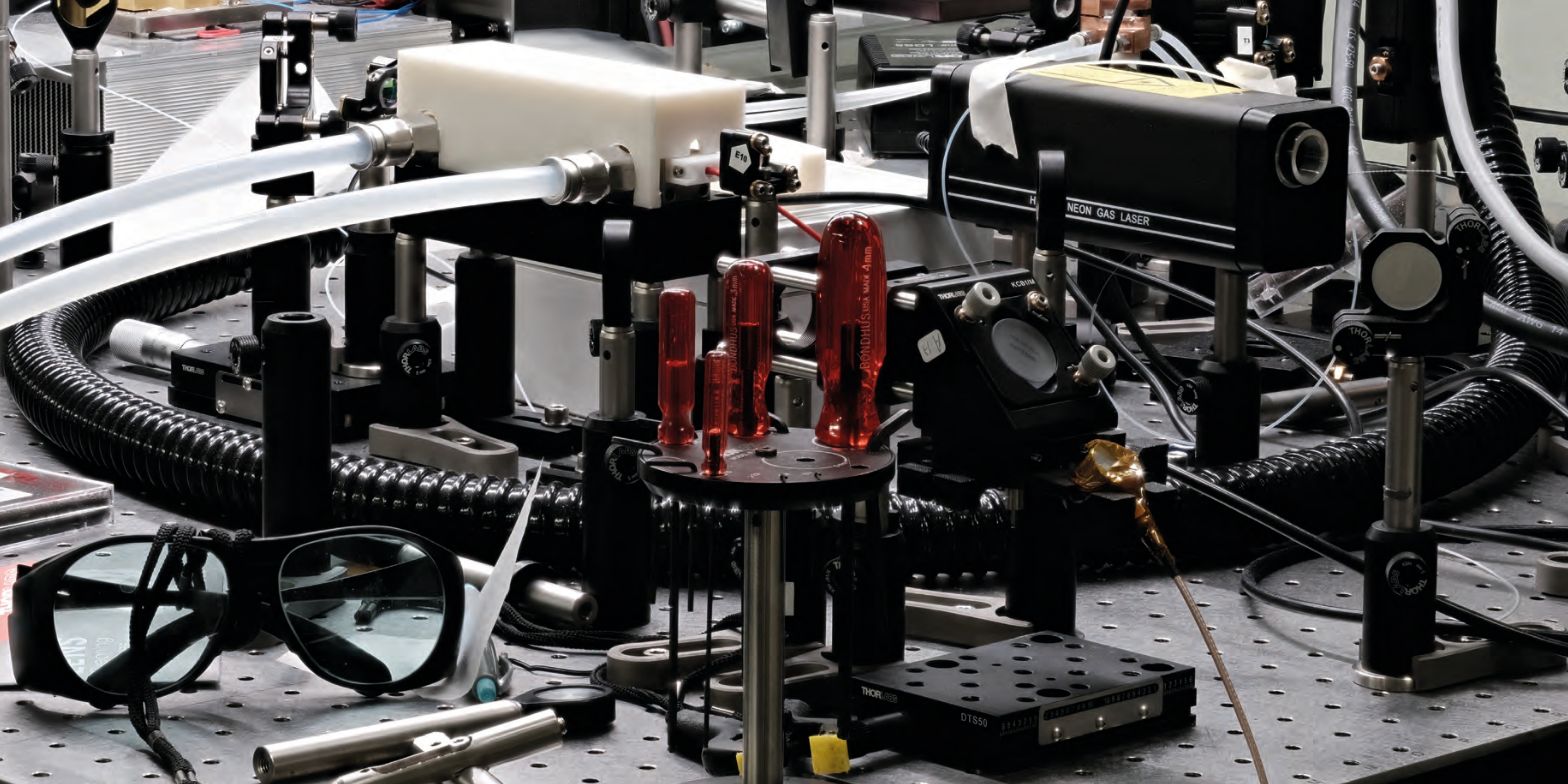


Universität
Basel

Departement of
Biomedical Engineering

MIRACLE
MINIMALLY INVASIVE ROBOTIC SURGERY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Imagine a surgical robot hanging from the ceiling of an operating room. It smoothly collaborates with the surgeons, is able to cut bone with unseen precision in all kinds of shapes, and to place smart implants in a minimally invasive way. This is our mission.

We are MIRACLE[II], a research project located at the Department of Biomedical Engineering (University of Basel) and funded by the Werner Siemens Stiftung. We bring together researchers from computer science, engineering, robotics, laser physics, surgery, and other disciplines to launch bone surgery into the space age.

We are committing ourselves to this goal because osteotomy can be a truly bloody affair that occasionally requires the application of considerable mechanical force causing collateral damages. We want to change this by going minimally invasive, maximizing precision and safety, and minimizing cut size as well as applied forces.

The heart of this system is a laser. Its light can be guided through a small incision to cut bone minimally invasively. The laser is controlled and operated by the surgeons through a minimally invasive robotic endoscope. Planning is done in virtual reality, monitoring in augmented reality. 3D printers are used to create patient-specific implants made from customized materials. This is our technological layout.

To make osteotomy minimally invasive, we must develop new solutions for all these four technologies and integrate them in one modular system. Obviously, this is a bold endeavor, which is why we see ourselves as **the Mars Mission in the field of medical robotics research**. Welcome to the MIRACLE[II] Project.

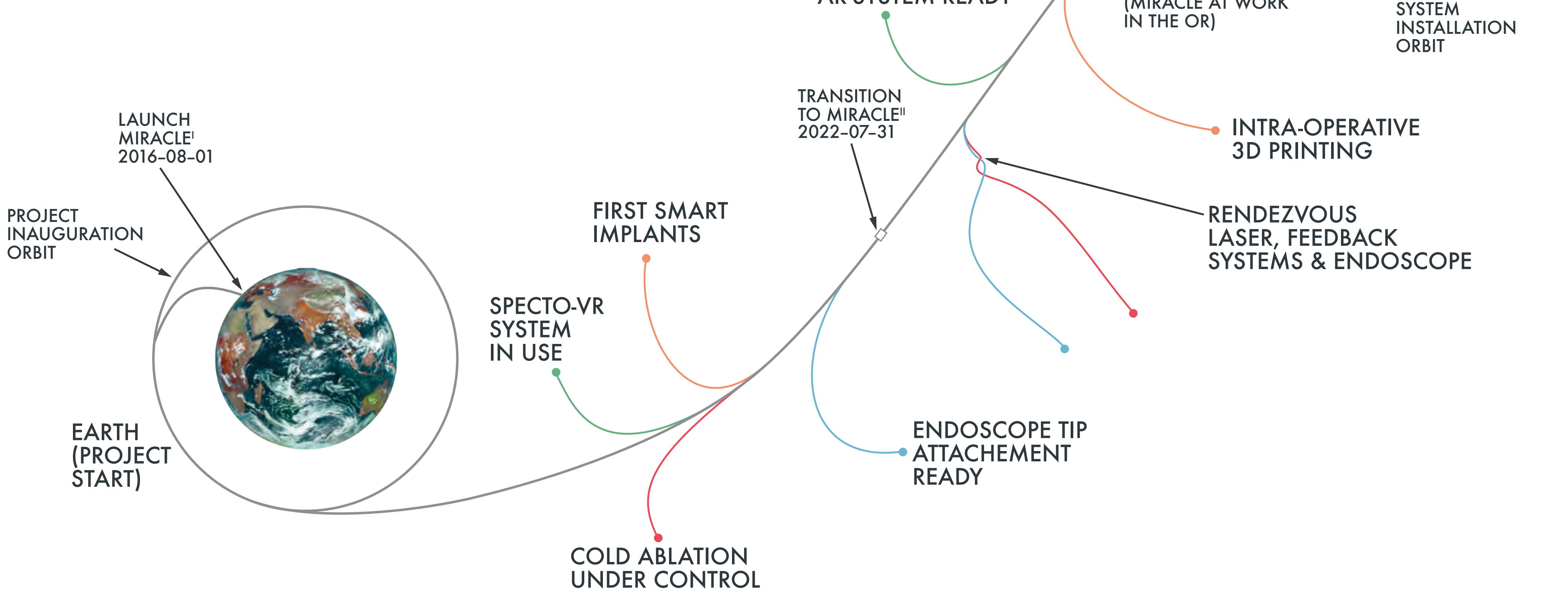
Prof. Dr. Philippe Cattin
Prof. Dr. Georg Rauter
Prof. Dr. mult. Florian Thieringer
Dr. Ferda Canbaz

MIRACLE II

DEPARTMENT OF BIOMEDICAL ENGINEERING | 2022-08-01

MIRACLE^{I} 2016–2022 | MIRACLE^{II} 2022–2027

PROJECT MIRACLE$^{I/II}$ ‹MARS MISSION› PROFILE



Research Architecture Mimics System Architecture

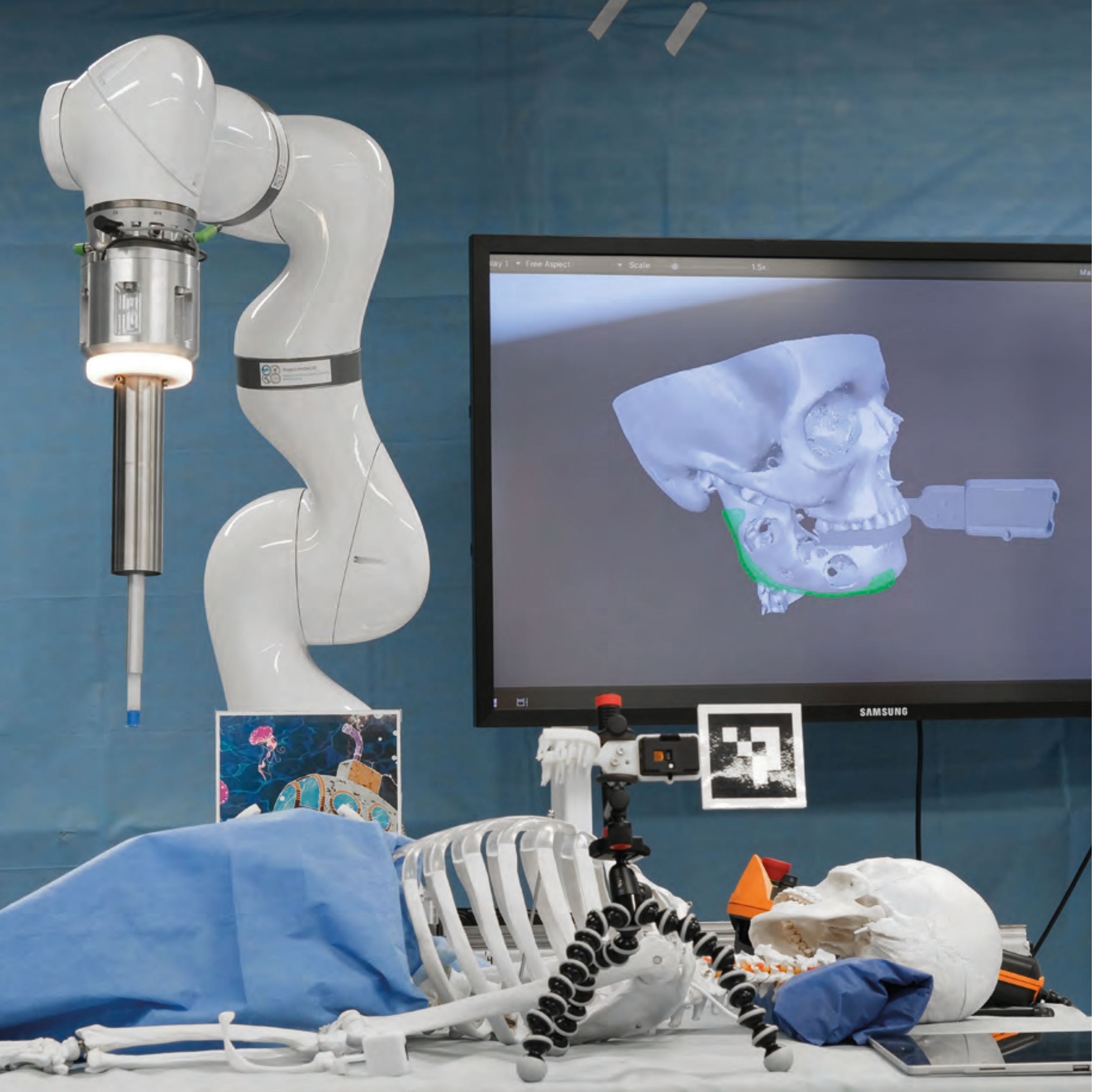
4 KEY TECHNOLOGIES, 4 GROUPS

The MIRACLE[II] System combines four key technologies: virtual and augmented reality, medical robotics, laser, and 3D printing for a novel surgical system. These four elements are developed by four research groups. The project architecture thus mimics the system architecture.

We have maintained this construction principle right through to the individual PhD projects. They are matched to each other like puzzle pieces, which we put together bit by bit, but which also perform as stand-alone solutions. Therefore, the group architecture also anticipates the system architecture in terms of modularity. The puzzle is well underway, so we can see the future of osteotomy more and more clearly every day.

The cooperative structure of the four groups realizes the ideal of transdisciplinarity: Researchers from different fields, like computer science, engineering, laser physics, 3D printing and surgery, work on their respective tasks together with their group members. Here, they act as specialists. At the same time, they work with researchers of the other fields on the combination of different technologies. There, they act as generalists.

This constant change of roles and perspectives enables us to ensure that the individual elements are well developed and work together smoothly— which is a prerequisite for the success of bold projects such as a Mars mission or minimally invasive laser osteotomy.



Group I: Planning & Navigation

TO MAKE A PLAN AND SEE IT THROUGH

A spaceship orbiting around Mars is severely damaged. Dozens of simultaneous warnings create an overwhelming cacophony of alarm tones. We, the audience of this science fiction movie scene, can experience what it feels like to be flooded with information amidst a life-threatening situation. From such experiences, we know a bit of the feeling that pilots and surgeons alike are afraid of.

Spaceflight and robotic surgery, thus, share a research question: What does a pilot, or, in our case, a minimally invasive robotic surgeon, need to get a useful picture of the situation at any given time? One way to do this is to move as much of the information processing as possible to the pre-launch period. The plan the surgeon develops during this phase certainly must correspond as closely as possible to whatever may happen later. This requires providing all available data in a way that the surgeon can piece together a usable, clear, and accurate picture of what is coming. The Planning & Navigation team has identified Virtual Reality as the most effective way to achieve this.

When the surgery has started, a system is required that provides the exact information needed in any given situation to keep the surgeons well informed at all times. Here, our tool of choice is augmented reality, which enables pinpoint navigation and a flow of information that always remains manageable. If we succeed in developing these two specialized systems, instead of a cacophony of alarm tones, we will hear only the busy silence of focused work.

Surgical Planning in Virtual Reality.

THE ART OF PLANNING

Surgery planning means to learn to distinguish the important from the unimportant features in the patient data as quickly as possible without missing any critical details. This is easier said than done because there are many factors to be considered.

VIRTUAL VISION

Our solution is called SpectoVR. Basically a link between the hospital data bank and the imagination, it allows several surgeons to meet simultaneously in virtual reality, inspect high-resolution 3D models of the patient from all sides and in all possible ways and determine the best course of action. This system is already in use at the University Hospital Basel, not only for surgery planning, but also for patient consultation and education. In addition, we are currently developing a surgical simulator by integrating haptic feedback technology into SpectoVR to further minimize the likelihood of complications.

SpectoVR brings patient data closer to the imagination than ever before.

MINIMALLY INVASIVE SEEING

For a minimally invasive surgeon it is a pity that humans are not transparent. Intraoperative CT scans can only be made a few times during surgery, and the endoscope camera only provides a very restricted view. But how can we know what is happening if we cannot see it?

In addition, we also need to keep track of the exact shape of the entire endoscope during surgery, to make sure that the procedure is executed exactly as planned and the adjacent tissue is affected as little as possible.

SHAPE SENSING+AR

To get this data in real time, we are developing a system to monitor the shape and location of a glass fiber inside the endoscope. Through augmented reality goggles, the surgeons then can see the entire endoscope “in” the anatomical environment together with selected additional data. Both are visible as overlay projections in transparent glasses. This way they can sense immediately if something is not going according to plan and directly initiate the necessary corrections without having to refer to any further data.

Group II: BIROMED-LAB

THE ENDOSCOPIC JOURNEY

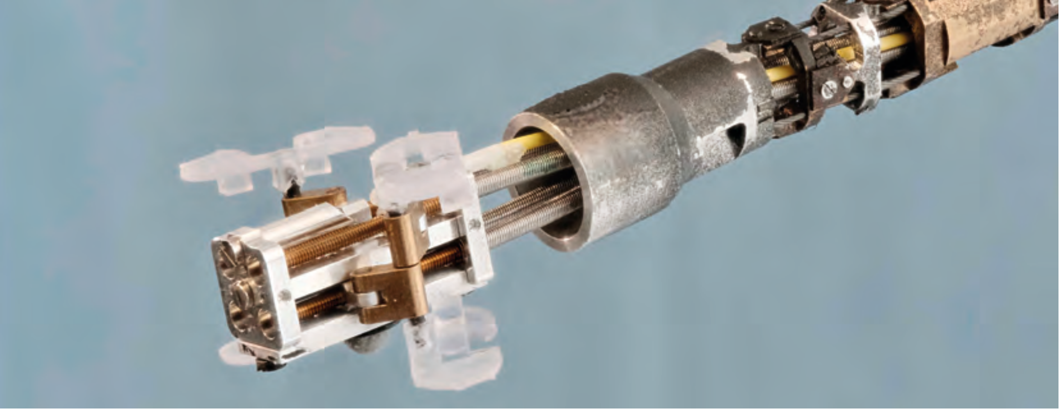
If the MIRACLE[II] Project is a Mars Mission, then the robot of the BIROMED-Lab (Bio-Inspired RObots for MEDicine-Lab) is the space program that takes the probe out there and lands it softly on the surface.

Like an interplanetary rocket system traveling into space, our robot is confronted with similarly diverse requirements on its journey through the body. It, therefore, consists of different components: Outside the body, the robot must be mobile enough to reach the entry site without getting in the way of the surgeons.

Once inside the body, a robotic endoscope must travel the path to the surgical site as determined in the planning without harming surrounding tissue. On site, another robot must attach itself to the target location so that it can move smoothly across the target path and direct the laser and other tools.

Depending on the situation, the robot positions the laser either autonomously or manually. But since no hand is steady enough to control the laser manually, we need a special input device. It scales down the surgeon's actions, so that when their hand moves one centimeter, the laser blade moves only one-tenth of a millimeter.

The OR can be compared to a mission control center, where the surgeons monitor and control the processes deep inside the body with augmented reality headsets. They are constantly adjusting all parameters of the probe, performing the endoscopic journey through the body with more precise control than a human alone could achieve under the same conditions.



A prototype of the endoscope.

SURGICAL CHOREOGRAPHIES

Although our “trip to Mars” is only a few centimeters long, we still perform our own docking maneuver by bringing the endoscope to the entry point at a precisely defined angle. The tricky part is that our robot has to regularly move to avoid obstructing surgeons without changing the angle of entry.

For this we will use a robotic system that consists of enough independently rotatable parts to provide the flexibility we need. To require as little space as possible, it will then be suspended from the ceiling.

BIO-INSPIRED

MIRACLE^{II}'s vehicle for the journey inside the body is inspired by the human hand. All the muscles are located in the palm and forearm, while the fingers are only moved by tendons. This is the principle of our bio-inspired endoscope. All the engines sit outside and apply forces through the endoscope by a number of tendons. That way we can minimize the size of the endoscope so that it fits into the minimally invasive incision and perform more complex maneuvers than a finger.

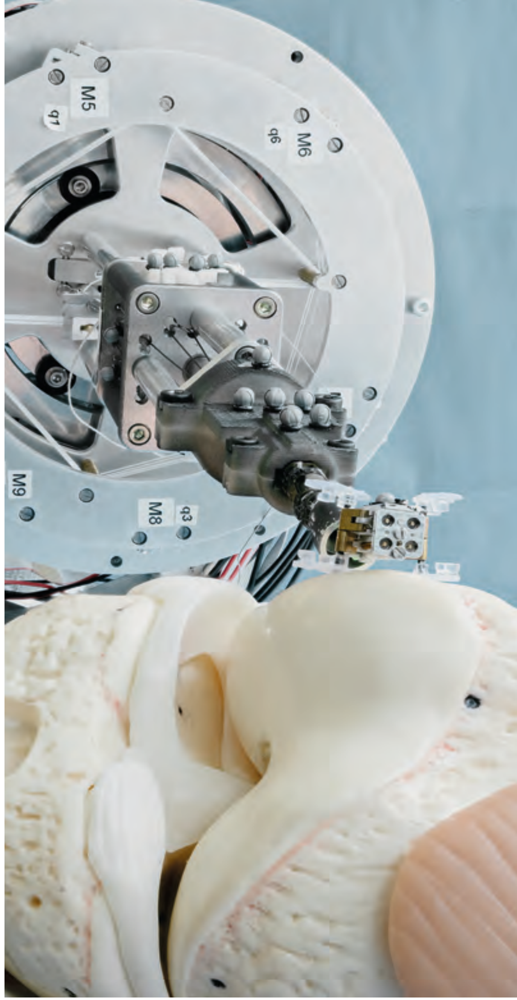
THE SOFTEST TOUCH

As soon as we are inside the body, the system requirements change substantially. Now, it is no longer a matter of avoiding the surgeons’ elbows, but the extremely vulnerable tissue of nerves and blood vessels.

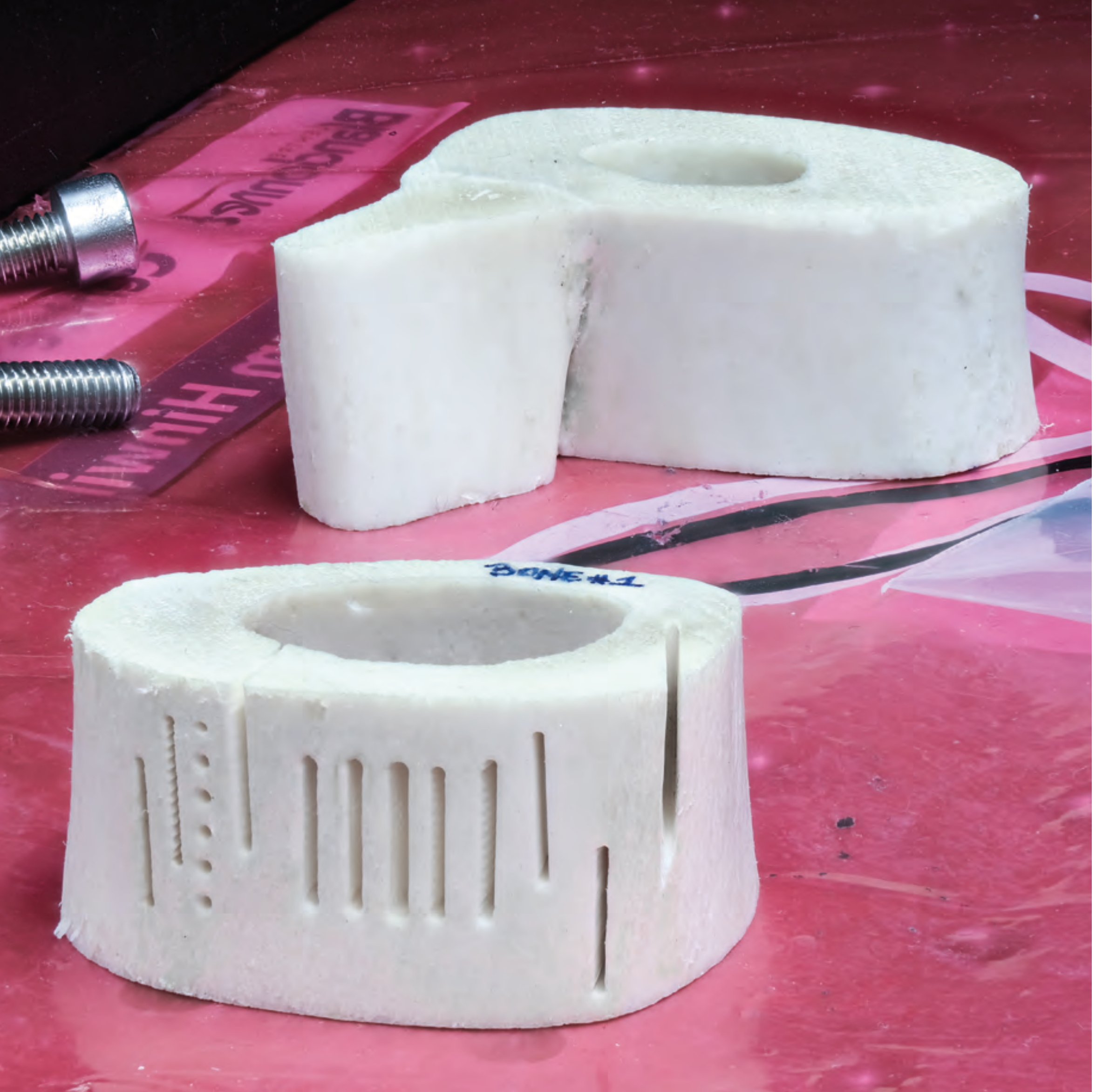
For this the endoscope is equipped with feedback systems that interrupt the movement if necessary. In addition, its materials have different degrees of softness and pliability, so that it can be easily deflected by the tissue.

ON SITE

When the endoscope tip has finally reached its target, a new challenge arises. Now the tip needs to land, stabilize, and travel short distances to secure the laser to work ultra-precisely despite movements caused by the patient or the surgeon. For this, the endoscope tip will anchor itself on site on the bone and thus maintain its position relative to the target area. Now, the laser cutting can begin.



The probe has landed on a model of a knee.



Group III: BLOG

A GENTLE AND CAUTIOUS LASER

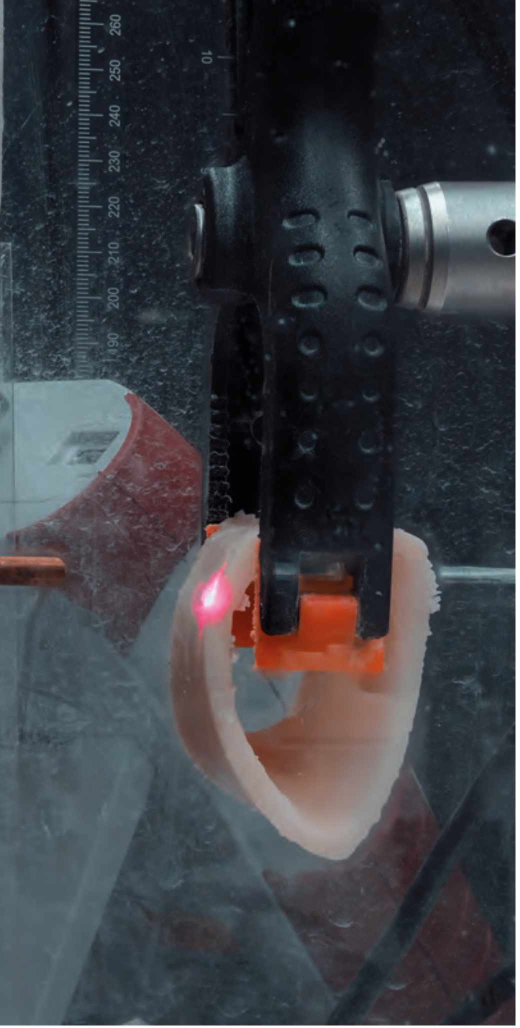
Now that we have landed on Mars, that is, the bone to be cut, the laser of the BLOG (Biomedical Laser & Optics Group) begins its work and cuts bone. It may come as a surprise that it can do this much more gently and cautiously than the tools which are currently in use in bone surgery.

The bone saw, for example, is a comparatively crude tool. It doesn't cut the bone, it grinds it, thereby generating such high temperatures that the bone is charred on the friction surfaces. Due to the design of the saw, no shapes other than a straight line can be cut, and chances are very small that the surrounding tissue stays intact.

The surgical drills are not much better. They can create more complex geometries, but they also crush the bone and overheat it. And then, none of these tools can be used in minimally invasive procedures, which is why osteotomy, in some respects, is stuck in a pre-modern era.

The laser has the reputation of a destructive weapon that leaves nothing but death and disaster in its wake. But in fact, it is the solution to all the problems mentioned above. Laser cutting can be done cool enough to keep the cut surfaces completely intact. It can generate a feedback signal that we can use to keep it from harming surrounding tissue. It can create complex cutting layouts that we can use as fits for the implants. And we can put it in an endoscope!

Therefore, we consider the laser as the most important prerequisite to launch osteotomy into the space age.



Laser bone cutting experiments in the laser lab.

A NEW RHYTHM

Saws and drills grind the bone at high temperatures, ok. But what does a laser do instead?

When a laser pulse hits (moistened) tissue, it causes the water to evaporate, which also removes a layer of tissue. The temperature of this procedure is low enough to keep the surrounding tissue unharmed. After the first laser pulse we remove detached material and take some measurements to make sure that the next pulse will hit the right tissue. Then the bone is re-moistened, and the process starts all over again. This is the rhythm of the MIRACLE^{II} system.

NEW SHAPES

In carpentry, the dovetail shape has been used for thousands of years to create very reliable joints without nails or screws. With the laser we create similar shapes to connect the bone to the implant. Due to such “functional cuts”, the implant will last longer, and the patient will feel much better right away.

To develop medical lasers, you have to love being surrounded by lots of technical equipment.

SUPERHUMAN PRECISION

Miraculously, the laser can also be used for measuring. The measuring laser creates a plasma, the color of which can be used to identify the tissue type. If the system detects the wrong tissue, the cutting laser immediately stops.

A second safety system can see a bit into the future. It uses the fact that light is reflected not only from the surface of the bone, but also from layers directly underneath. This way we can foresee which tissue the laser pulse would hit after the next one.

Safety systems like these are pointless in current bone surgery because the saws, drills and chisels cannot be controlled in the submillimeter and millisecond range. In the MIRACLE^{II} System, they help us to cut the bone and only the bone, leaving all other tissue completely intact.

So, we are not only landing on Mars, but we are performing tasks there that far exceed the capabilities of a human being: Minimally invasive, hyper precision, minimally harming functional cuts, ready for patient specific implants.

Picture: M. Maintz/Swiss MAM

Group IV: Smart Implants

UNSEEN PATIENT SPECIFICITY

Payload sections in space rockets are rather small. So, scientists have to build their probes to fit in there and unfold only on site. The MIRACLE[II] System has a similar bottleneck in the form of the small minimally invasive incision. Not only do the tools have to fit through it, but also the implants. Bigger ones can't get to the target in one piece. But how else? Here is the trick.

As you have seen, we can cut complex shapes into the bone, so that implants can be clicked in like one puzzle piece into another. For implants too big for minimally invasive surgery, we want to use the same method: They will be designed as three-dimensional jigsaw puzzles, with their pieces being small enough to fit through the minimally invasive incision. The puzzle can then be assembled inside the patient without loss of stability.

But that's not the only reason why we call our implants "smart". We can adapt their shape as well as their materiality precisely to the specific needs of the individual patient. We can install sensors that send information about the condition and acceptance of the implants to the outside. And we are already able to print them directly at the point of care, thus avoiding lengthy manufacturing processes off-site.

One day we want to be able to design, test, print, and insert these implants minimally-invasively, without a single screw, in one fast workflow, directly on-site, so that patients regain the functionality of the affected bone as fast as possible and with minimum pain and effort.

3D printed implant that stabilized a fractured jaw.

THE CLOSEST ENCOUNTER

No technical device comes as close to the human body as an implant. For it to really help the patient, its entire surface must be perfectly adapted to this closest of encounters. 3D printing has brought us closer to this goal than any other technology before.

With it, we can control the properties of the implants so precisely that they fulfill their mechanic function and at the same time promote effective healing. This requires a perfect fit and a mixture of materials that is tailored to the individual patient.

NEW TEXTURES

Just like large space missions, truly patient-specific implants can only be realized in an institutionally, technologically, and socially favorable environment.

This is why we are interested not only in developing the material textures of patient-specific implants, but also the social, institutional, and technological texture of the network capable of producing and inserting them in a single workflow. We are addressing several of the major interfaces of such a network.

THE POINT OF CARE

One important property of this infrastructural texture is proximity: The closer the various physical elements are to each other, the faster and better we can help the patients. We have already installed specialized printers in the surgical site of University Hospital Basel. Soon we will be able to manufacture patient-specific, 3D-printed implants on site, avoiding error-prone communication processes and to speed up the process.

TRANSLATION

Another important property of a favorable environment is perfect synergy between all parties, for example between research and clinical practice. This is why the Smart Implants Group is headed by a cranio-maxillo-facial surgeon and the team consists of researchers and clinicians alike. Through this integration we ensure that ideas can flow freely between bench and bedside and give birth to developments that really find their way to help the patients.

A minimally invasive implant in the operation room of the University Hospital Basel

Synthesis

BEFORE THIS DECADE IS OUT

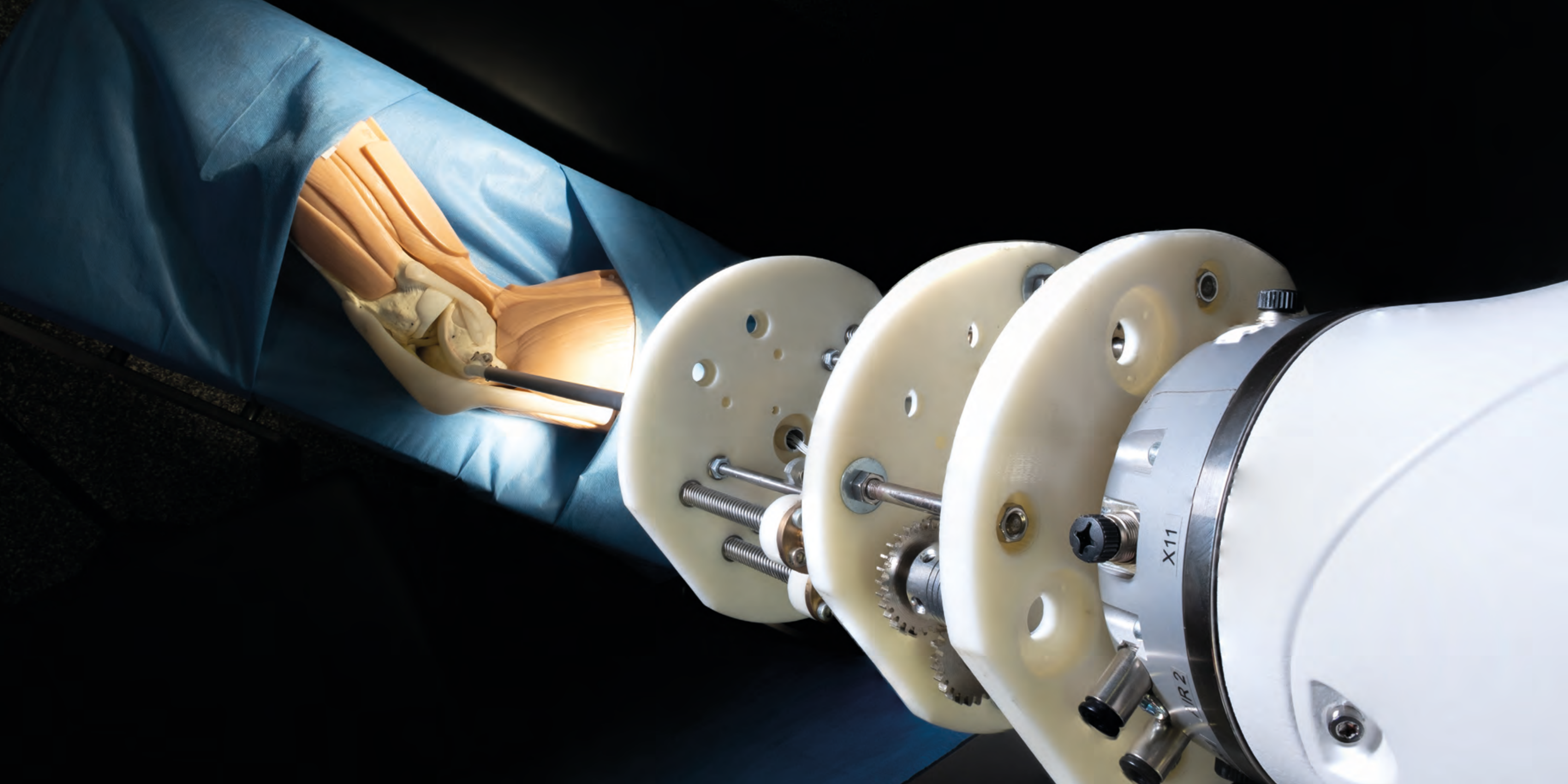
We are committing ourselves to achieving the goal, before this decade is out, of developing the technological solutions for Minimally Invasive Robot Assisted Computer guided LaserosteotomE.

One day, a patient may come to the University Hospital Basel because of pain the jaw. The radiologist may find a very rare tumor that needs to be removed and the cranio-maxillo-facial surgeons decide that the lost tissue needs to be replaced by a bio-implant.

The surgeons then would meet in virtual reality with a specialist in these tumors, let's say from New York, to discuss the best course of action. They would conclude that two dovetail shapes would be best to connect the implant to the jaw. This shape would be programmed into the robot, and the according puzzle implant would be designed, printed, and tested at the point of care.

The surgeons then would maneuver the robotic endoscope gently through soft tissue, dock at the target site, make the bone incisions as planned, and then retract. The implant would be inserted piece by piece, assembled and finally checked, before the minimally invasive incision would be closed again.

When that patient leaves the hospital with a fully functional jaw, almost no pain, and the best prospects for full recovery, the era of the bone surgery of our parents will have come to an end and a new era, the space age of bone surgery, will have begun.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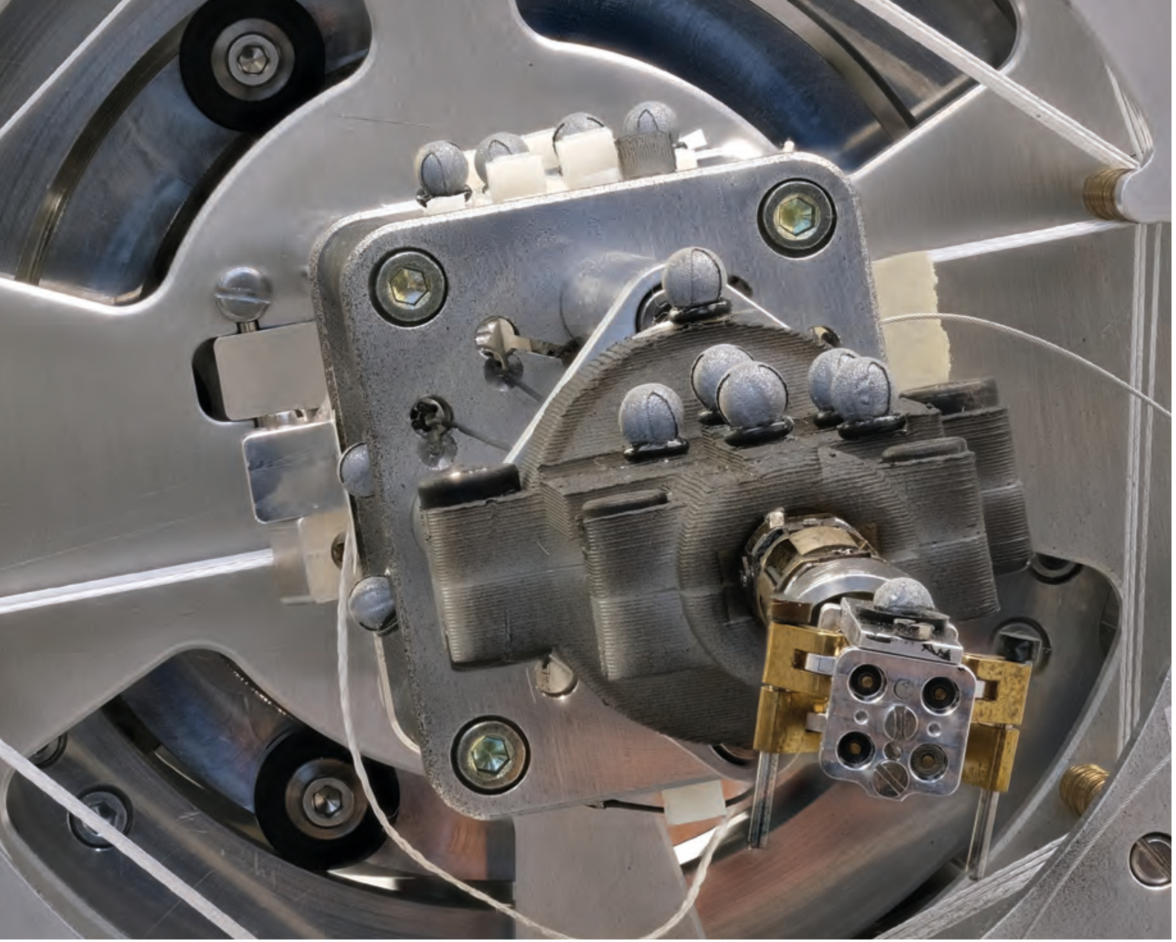

All pictures by Reinhard Wendler
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Leading House:

Universität Basel
Departement of Biomedical Engineering

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More than you ever wanted to know about the MIRACLE[II] Project: