Medical Robotics

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GVF-based control of cooperative systems for retinal surgery

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- some retinal pathologies could benefit from the insertion of a needle into a vein on the surface of the retina as a path for drug delivery; vein cannulation is a procedure which is not safe to perform clinically today, but would have great clinical utility if it could be done reliably

The occlusion is reached directly by the tool and then it injecting an anticoagulant(in this case but in general drunks)

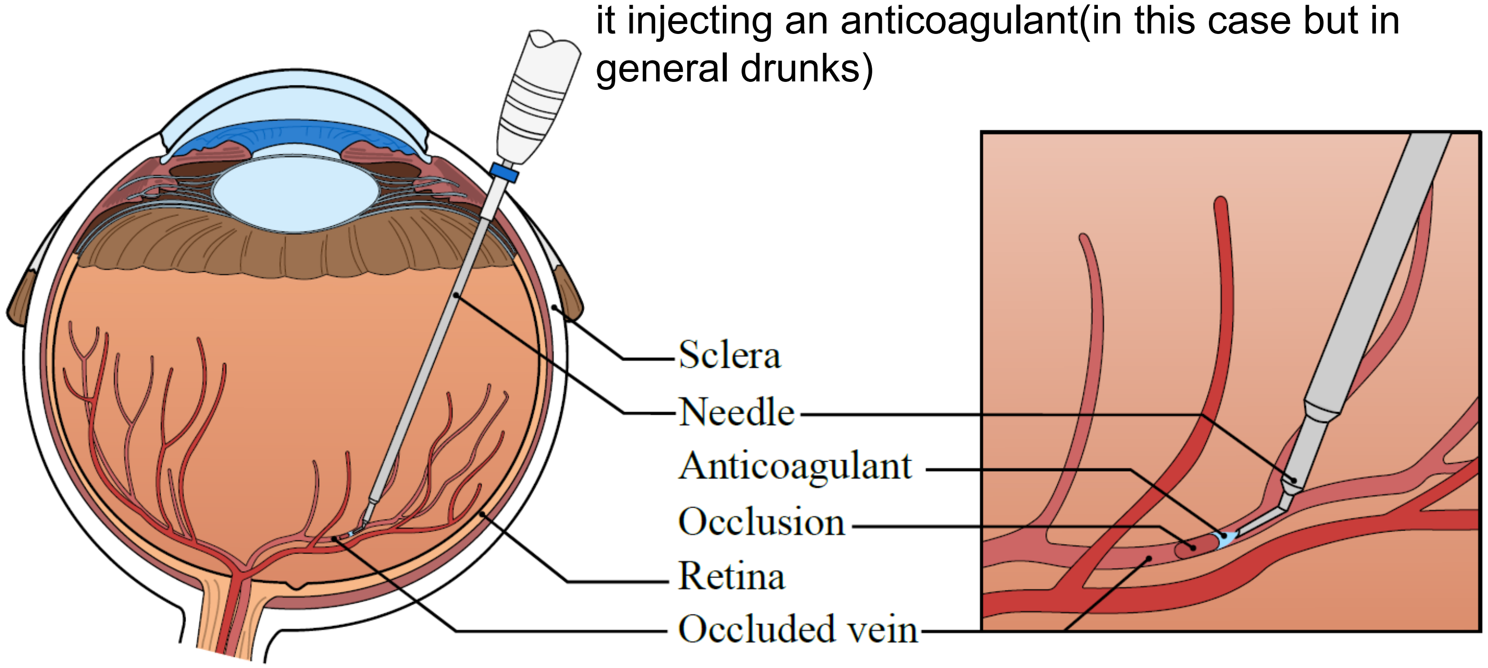
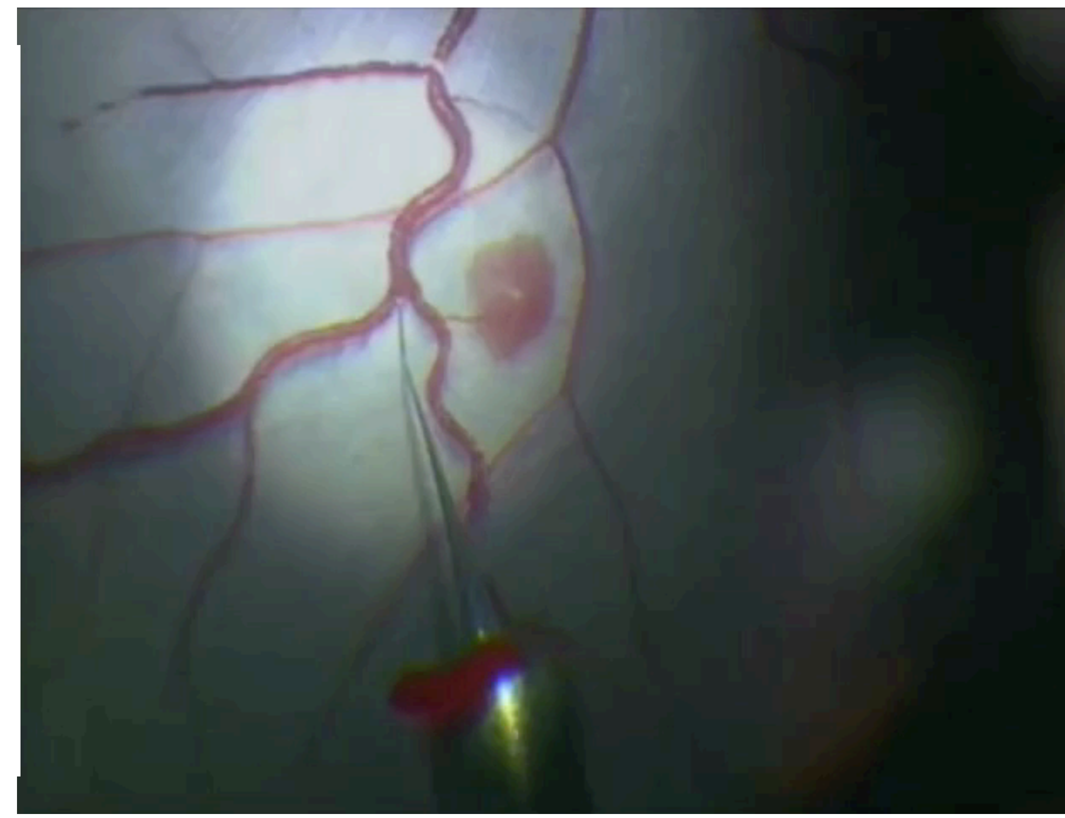


Figure 2: Retinal Vein Occlusion treated with retinal vein cannulation.

This procedure is not safe to perform today



- the outer diameter of the blood vessel is on the order of $100\,\mu$m (root mean square amplitude of hand tremor has been measured to be $182\,\mu$m)

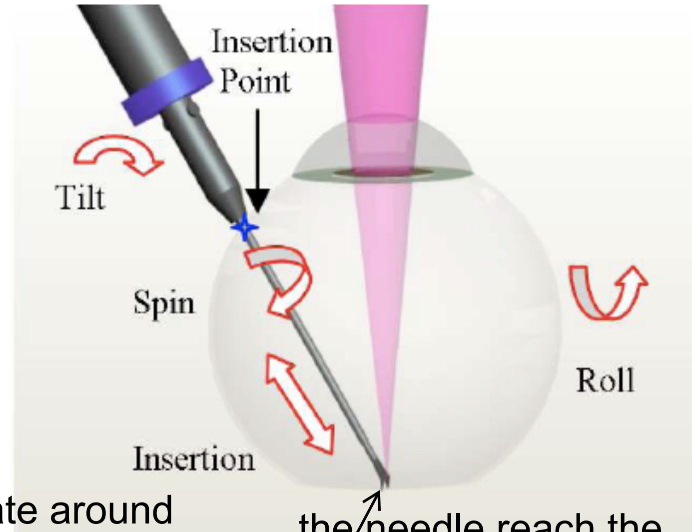
- the difficulties related to manipulation on a microscopic scale can be reduced with the use of cooperative systems the robot helps in keeping the end of the surgical steady so removing the noise.

- the John Hopkins University Steady-Hand Robot (SHR) was designed to cooperatively share control of a surgical tool with the surgeon while meeting the performance, accuracy, and safety requirements of microsurgery

with a human

needed DOFs in tool positioning for eye surgery

To find which is the most appropriate kinematic architecture, first of all, we need to define how many dof we need to execute medical surgical procedure



It's necessary to rotate the needl around its axis(roll pitch yaw) and also to spin(change the orientation) about the fixed point. So we need 3-dof just for rotation at the entry point and then for insertion

- approach: at least 3 DOFs
- insertion: 3 DOFs (one translation, two rotations)

overall we need 4-dof

to enter the eyes

to insert the needle

- retinal surgery: 4 DOFs (three rotations, one translation)

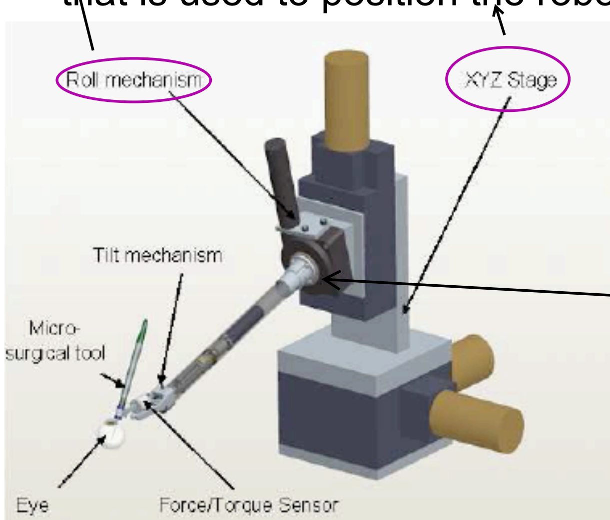
this is guidance virtual features

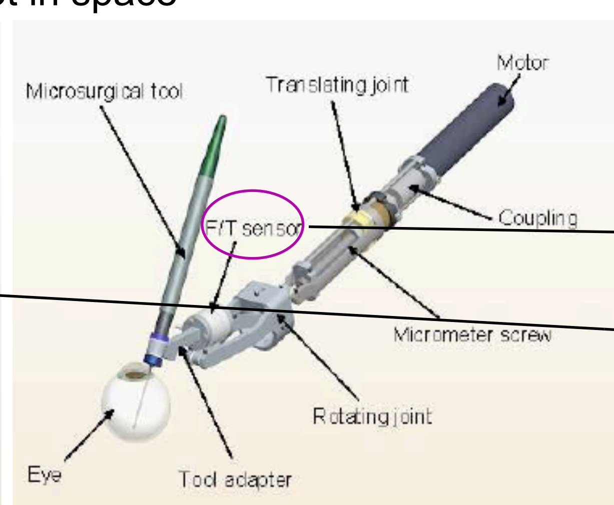
to rotate around the axis

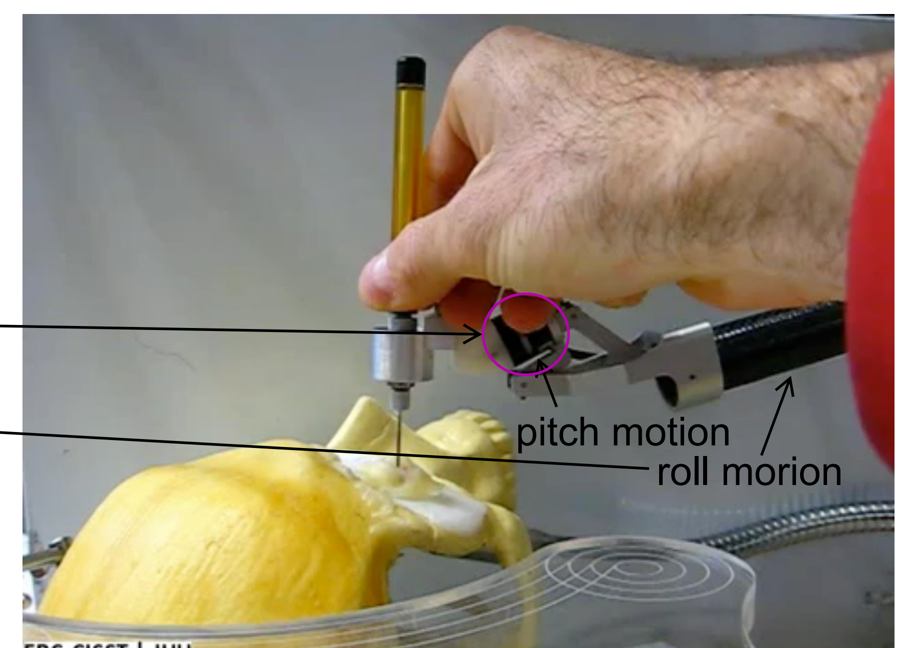
the needle reach the back of the retina

in addition, the retinal surgery phase requires tool motions to be constrained by an insertion point $\Rightarrow$ an RCM is needed

that is used to position the robot in space







pitch motion

roll morion

Here we see how the control is achieved and how the RCM constraint is satisfied

VF-based control of the SHR

- given sensed handle forces and torques $f \in \mathbb{R}(6)$ exerted by the operator, a tool velocity screw is computed as

starting equation

veocity of the tool tip $\rightarrow$ $$v = Gf$$ force

this eq express the relation between the interaction force and the velocity of the body that is in this case the velocity of the tool. The velocity is obtained in response to interaction forces applied.

constant gain

the matrix $G \in \mathbb{R}(6 \times 6)$ determines the relative gains of the sensed forces, and thus permits shaping of the motion response to force inputs

the objective of the control problem is to design the G matrix

- the virtual RCM point is achieved by minimizing the cost function

jacobian of the point ph

First we see how the RCM is satisfied

$$\boxed{||J_h(q)\Delta q - Gf||}$$

Ph is the point where the surgeon is in contact with the sirgical tool

here we are solving an optimization problem

what we want to find is the velocity

subject to the constraint

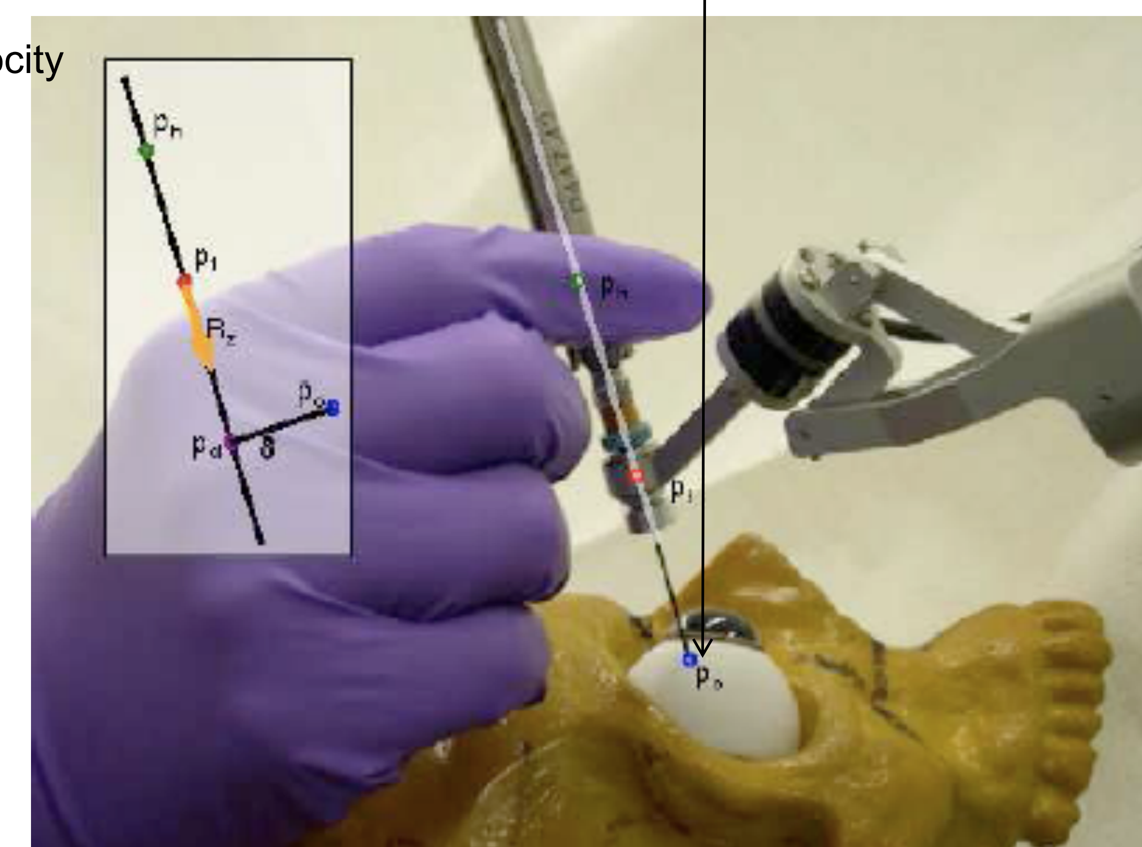
displacement

$$\boxed{||P_{cl} + J_{cl}(q)\Delta q - P_o|| \leq \epsilon}$$

current position of the RCM

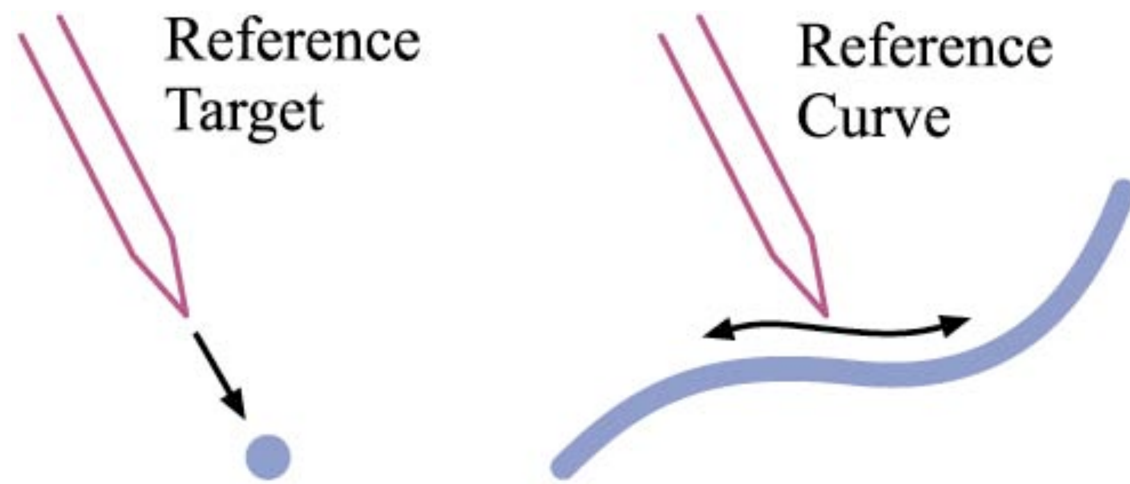
obtained by this eq

P_{cl} : a point on the robot tool closest to the virtual RCM P_o; $J_h(q)$, $J_{cl}(q)$: the manipulator Jacobians resolved respectively at the handle and at P_{cl}



for illustration, two main types of GVFs are considered

in this case the little tip is guided to the reference target



in this case the tool tip is guided along the reference curve

they can be combined for more complex tasks

GVF-based control of the first prototype of the SHR

- cartesian positioning device with ``virtual contact" between the robot tool tip and the environment modeled as

$$v = c\,f$$

which is an isotropic admittance-type device

- a VF generalizes this model to include anisotropic admittances

GVF on tool position

this matrix is a column vector with 3 components that are the coordinates of the point along the curve(it represents our guidance)

1. given a $3 \times n, 0 < n < 3$, time-varying matrix $\delta(t)$ with column rank n which represents the instantaneous ``preferred'' directions of motion for the tool tip

 - ($n = 1$: motion along a curve in space; $n = 2$: motion on a plane ...)

2. define the projection operator $\boldsymbol{D}_\delta \equiv \boldsymbol{\delta}(\boldsymbol{\delta}^T\boldsymbol{\delta})^{-1}\boldsymbol{\delta}^T$ on the subspace generated by $\boldsymbol{\delta}$

this will be a scalar

3. decompose $\boldsymbol{f}$

delta and tau have different direction

$$\boldsymbol{f}_\delta \equiv \boldsymbol{D}_\delta \boldsymbol{f} \qquad \boldsymbol{f}_\tau \equiv \boldsymbol{f} - \boldsymbol{f}_\delta$$

orthogonal to the original force F

$$\Rightarrow \boldsymbol{f}_\tau^T \boldsymbol{f}_\delta = 0$$

- the admittance model becomes $\boldsymbol{v} = \boldsymbol{c}(\boldsymbol{f}_\delta + \boldsymbol{f}_\tau)$
- the introduction of a new admittance $\boldsymbol{c}_\tau \in [0, 1]$ that attenuates the non-preferred component of the force input $\boldsymbol{f}_\tau$ results in

filters the unknown admissible components of the apllied force

$$\boxed{\boldsymbol{v} = \boldsymbol{c}(\boldsymbol{f}_\delta + \boldsymbol{c}_\tau \boldsymbol{f}_\tau) = \boldsymbol{c}(\boldsymbol{D}_\delta + \boldsymbol{c}_\tau(\boldsymbol{I} - \boldsymbol{D}_\delta))\boldsymbol{f} = \boldsymbol{G}(\boldsymbol{c}, \boldsymbol{c}_\tau, \boldsymbol{\delta})\boldsymbol{f}} \qquad (1)$$

- final control law in the general form of an admittance control with a time-varying gain
- the value of $\boldsymbol{c}_\tau$ determines the robot stiffness in non-preferred directions

  * $c_\tau = 0 \Rightarrow$ hard VF
  * $0 < \boldsymbol{c}_\tau < 1 \Rightarrow$ soft VF
  * $\boldsymbol{c}_\tau = 1 \Rightarrow$ isotropic admittance

the reference path is the path from the tool tip to the target

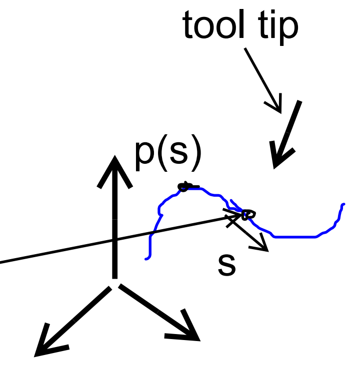
- *reference target*: the desired path is the segment joining the current tool position to the target point; the reference direction is computed as

$$\boldsymbol{\delta}_t(\boldsymbol{p}_a) = \boldsymbol{p}_t - \boldsymbol{p}_a$$

difference between the 2 point just illustrated

with $\boldsymbol{p}_a$ position of the tip in $\mathbb{R}^3$

the output velocity is computed from (1) by setting $\boldsymbol{\delta} = \boldsymbol{\delta}_t$



- *reference curve*: given the parametric expression of the reference curve

blue curves is parametrized by s

$$\boxed{\boldsymbol{p}(s) \equiv (x(s) \quad y(s) \quad z(s))^T,} \qquad s \in [0,1]$$

- determined the point on the curve $\widehat{s}(\boldsymbol{p}_a)$ which is closest to the ``tool tip''

$$\|\boldsymbol{p}(\widehat{s}(\boldsymbol{p}_a)) - \boldsymbol{p}_a\| = \min_{s \in [0,1]} \|\boldsymbol{p}(s) - \boldsymbol{p}_a\|$$

- the reference direction $\boldsymbol{\delta}_p$ is given by the tangent to the curve in $\widehat{s}(\boldsymbol{p}_a)$

$$\boldsymbol{t}(\boldsymbol{p}_a) = \frac{d}{ds}\boldsymbol{p}(s)|_{s=\widehat{s}(\boldsymbol{p}_a)}$$

$$\boldsymbol{\delta}_p(\boldsymbol{p}_a) = \frac{\boldsymbol{t}(\boldsymbol{p}_a)}{\|\boldsymbol{t}(\boldsymbol{p}_a)\|}$$

note: in this case (1) does not apply directly with $\boldsymbol{\delta} = \boldsymbol{\delta}_p$ because an initial offset would not be recovered $\Rightarrow$ introduce a correction term for the cartesian error $\boldsymbol{e}(\boldsymbol{p}_a) = \boldsymbol{p}(\widehat{s}(\boldsymbol{p}_a)) - \boldsymbol{p}_a$ the new direction $\boldsymbol{\delta}_c$ is defined as

$$\boldsymbol{\delta}_c(\boldsymbol{p}_a) = \text{sign}(\boldsymbol{f} \cdot \boldsymbol{\delta}_p(\boldsymbol{p}_a))\boldsymbol{\delta}_p(\boldsymbol{p}_a) + k_d \boldsymbol{e}(\boldsymbol{p}_a)$$

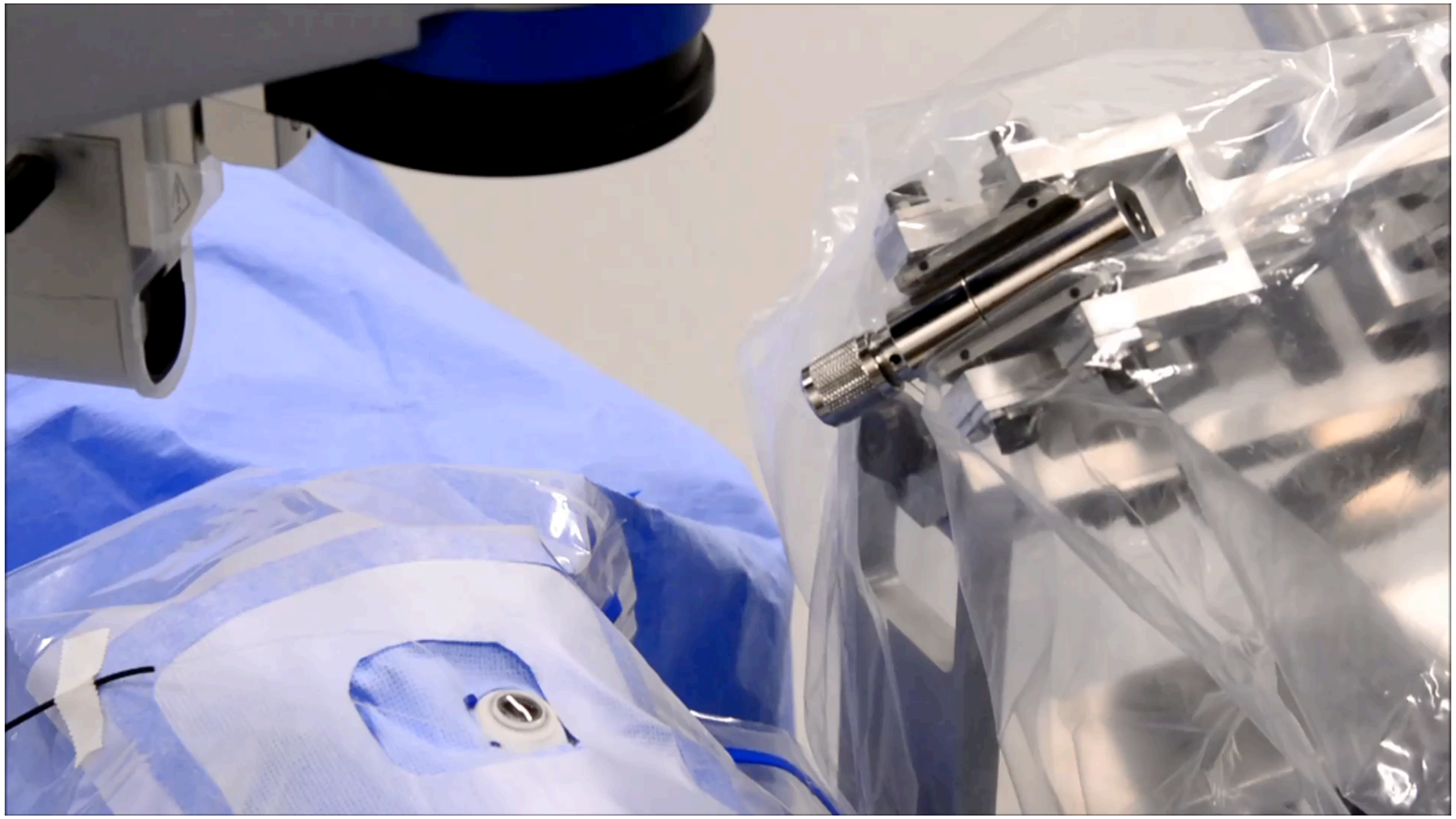
comments

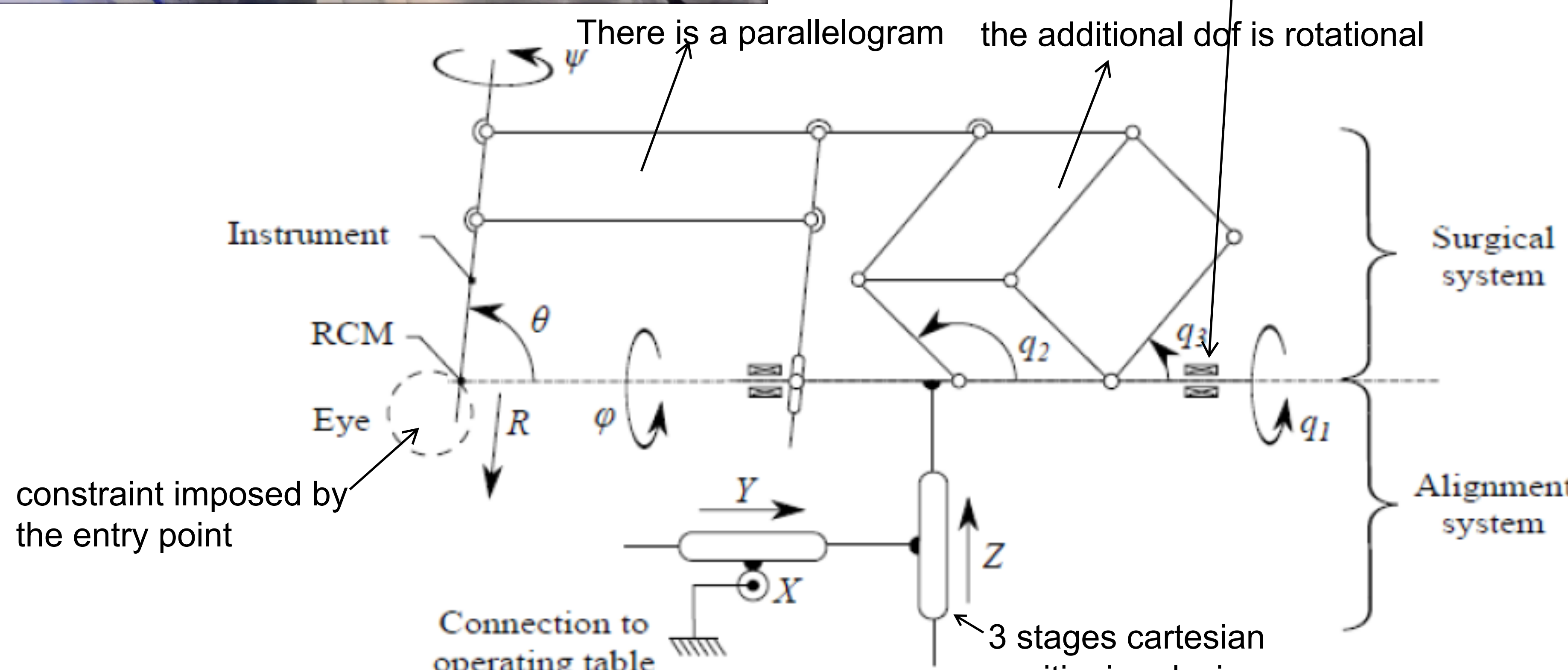
- using the assumptions that $\boldsymbol{\delta}$ is full rank and the human input force is continuous, the admittance control law (1) is guaranteed to converge asymptotically

what is convenient is to define a sphere around the target and when the surgical tool tip enters this sphere, we switch to a different control law.

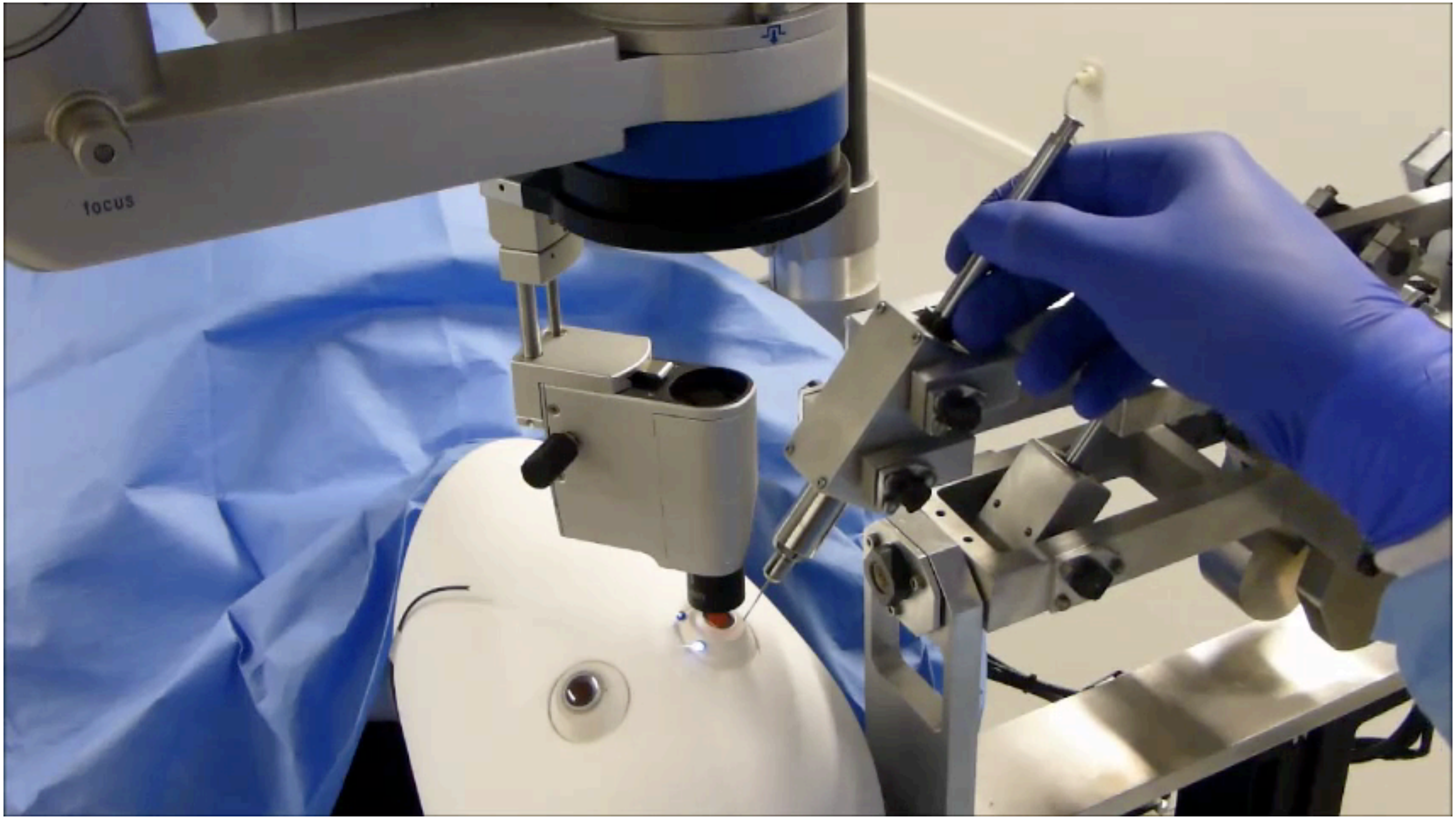
- in the reference target case, the rank constraint on $\boldsymbol{\delta}$ is violated at the target (ill conditioned near the target) $\Rightarrow$ it is convenient to define a spherical switching $S(\rho)$ with center at the target point and radius ρ: outside $S(\rho)$ the path following is active, inside $S(\rho)$ a different control scheme is activated
  - fix the direction and use that reference direction as the basis for a VF
  - switch to an autonomous motion (e.g., proportional control $\boldsymbol{v} = \boldsymbol{k}_c(\boldsymbol{p}_t - \boldsymbol{p}_a)$)
- the velocity discontinuities on the switching surface can be avoided by resorting to a VF-based acceleration control scheme
- it is useful for practical applications to extend this approach to confine the motion within volumes (tube around the reference path, cone with vertex at the reference point)

similar systems: world first application at University Hospitals Leuven



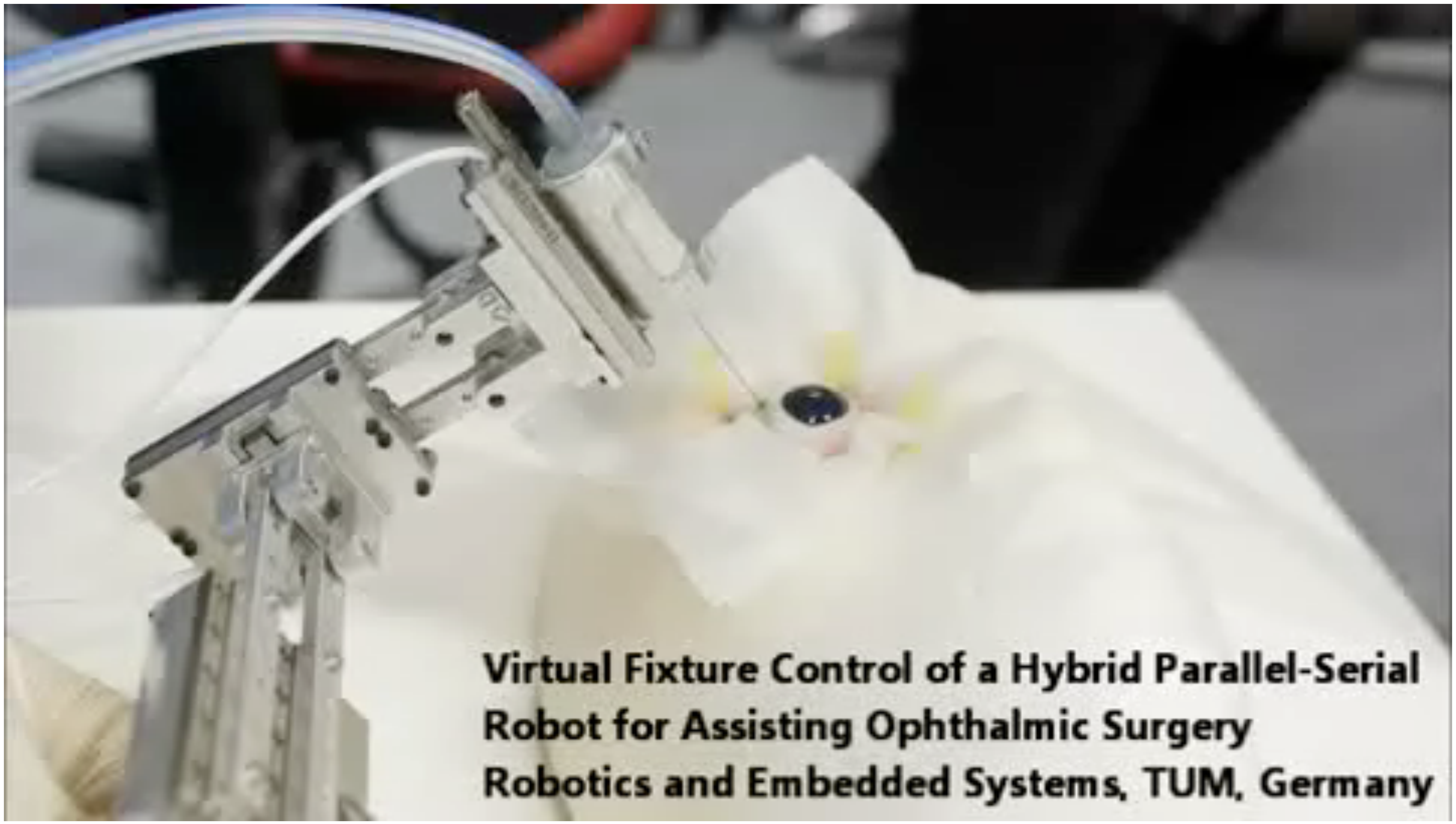


Robot developed at University of Leuven: RCM principle



similar systems: Robot developed at TU Munich

cooperation between the operator and the robot



similar systems: Micron

- active handheld micromanipulators that is based on high-bandwidth position measurements rather than forces applied to a robot handle
- fixtures are generated in real time from microscope video during the procedure

bibliography

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