Medical Robotics

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Task Control with RCM constraint

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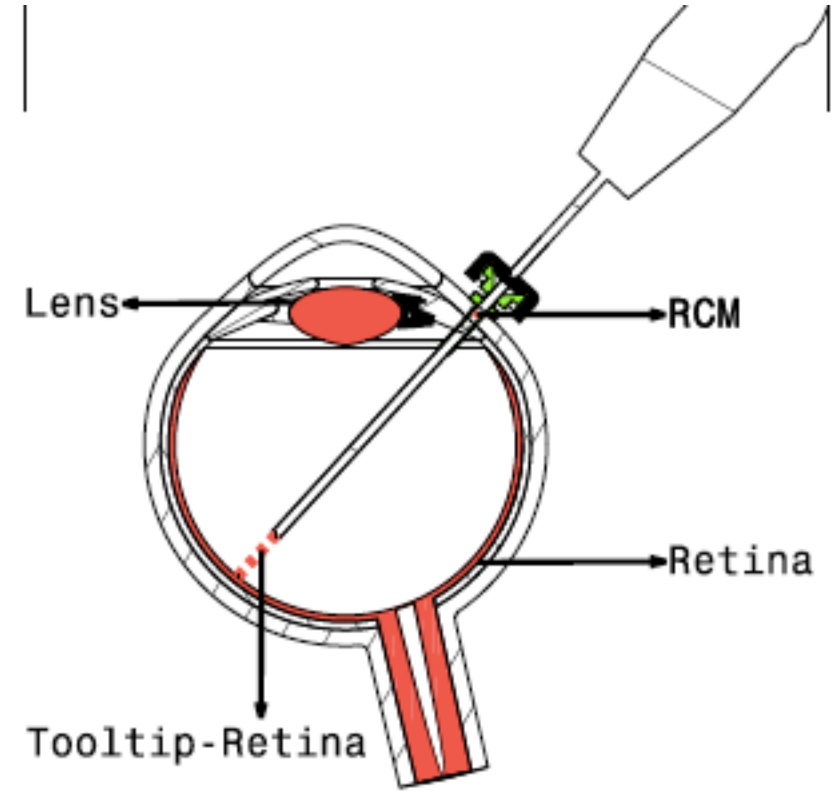
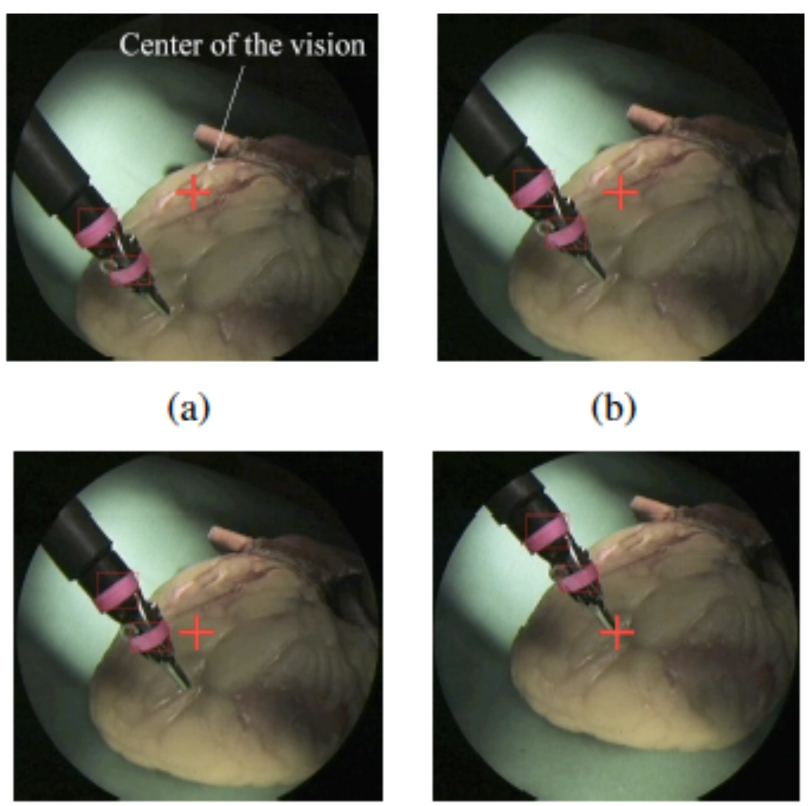
examples of surgical tasks subject to RCM constraint

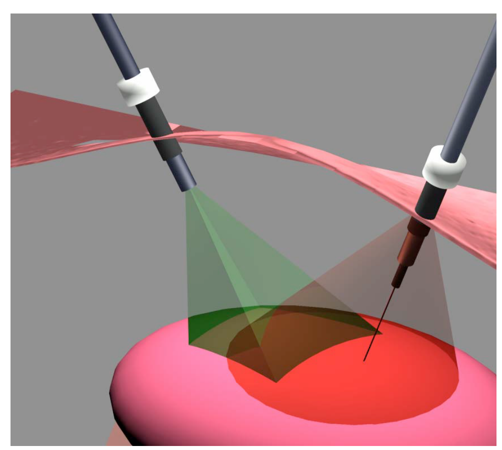
- control based on VF
- tool/endoscope vision-based control
- automatic suturing

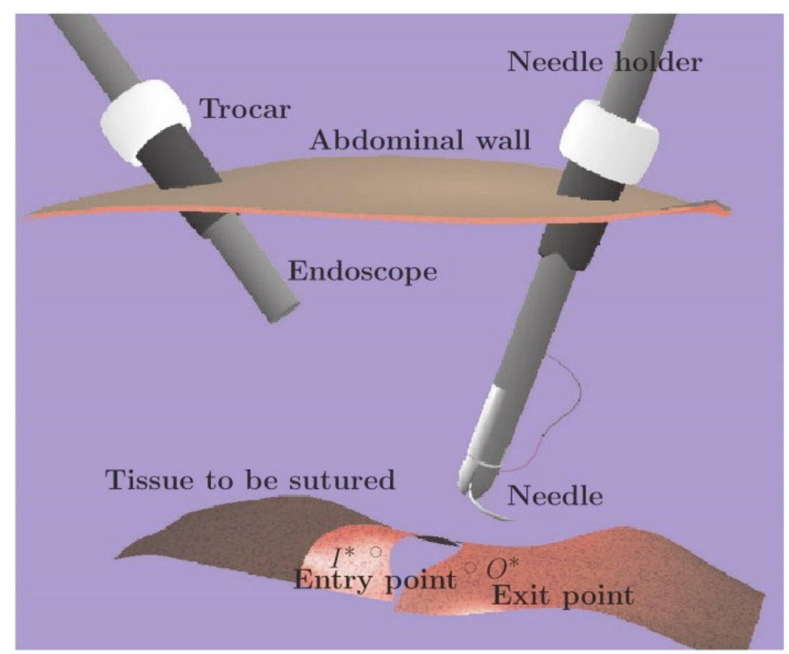


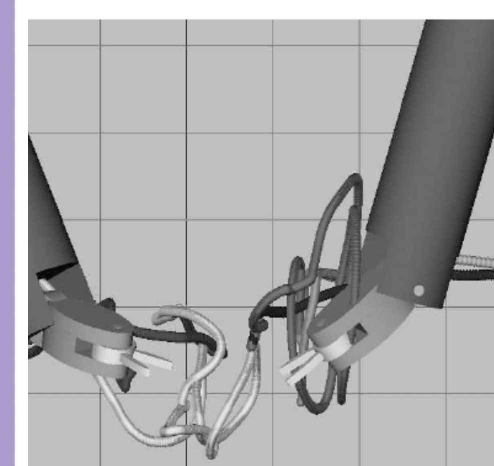


(a) (b)

(c) (d)







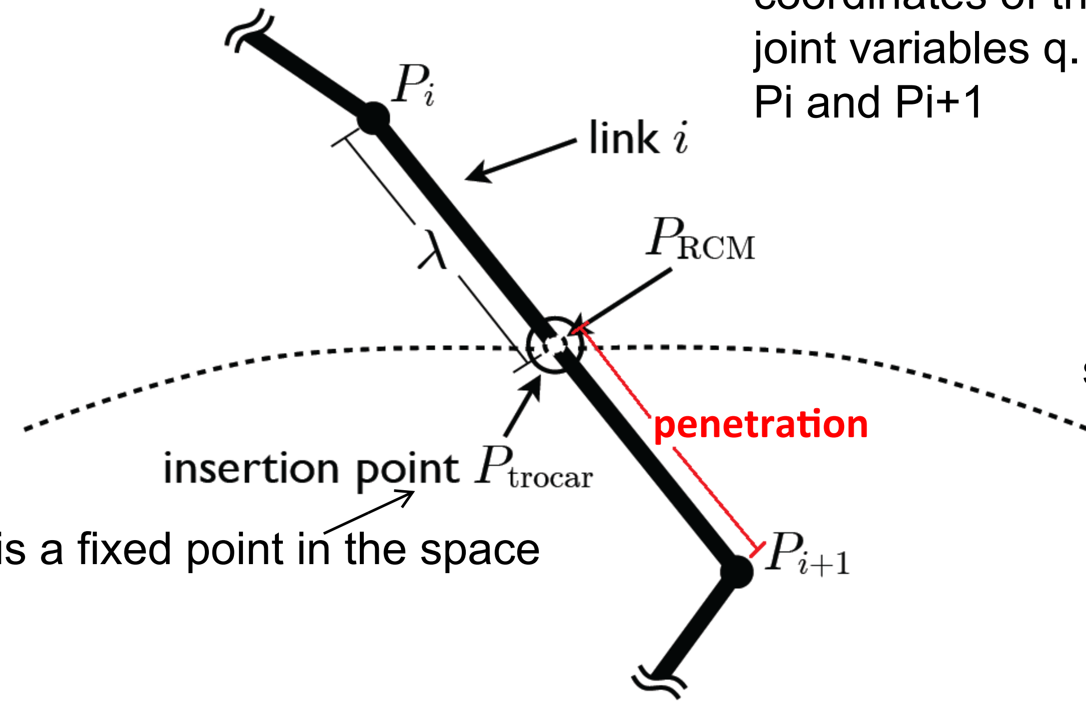
lecture's content

- general characterization of the RCM constraint
  - explicit model of the translational motion along the link axis
  - direct control of penetration
  - minimal information needed for registration
- RCM constrained motion planning
- visual task control with RCM constraint
- shared control of the Steady Hand with GVF and RCM constraint

REFER TO SLIDE 18 OF 04_KinDes BLOCK

RCM constraint

variable point on the robot link, but doesn't matter where this point in on the manipulator link, its cartesian coordinates should be equal to trocar. We write the coordinates of this point as a function of the manipulator joint variables q. We want to write this point in function of Pi and Pi+1



it is a fixed point in the space

this is a 3-dim vector

parametrized length according to lamda

normalized length of the link

$$\boldsymbol{p}_{\mathrm{RCM}}(\boldsymbol{q}(t)) = \boldsymbol{p}_i(\boldsymbol{q}(t)) + \lambda(t)(\boldsymbol{p}_{i+1}(\boldsymbol{q}(t)) - \boldsymbol{p}_i(\boldsymbol{q}(t))), \quad 0 \leq \lambda(t) \leq 1$$

I want pRCM is always coincident with Ptrocar. To impose it we need to provide a model of the motion of this pRCM.

this jacobian depends on q and lamda(usually the J depens only on q)

$$\dot{\boldsymbol{p}}_{\mathrm{RCM}} = \begin{pmatrix} \boldsymbol{J}_i + \lambda(\boldsymbol{J}_{i+1} - \boldsymbol{J}_i) & \boldsymbol{p}_{i+1} - \boldsymbol{p}_i \end{pmatrix} \begin{pmatrix} \dot{\boldsymbol{q}} \\ \dot{\lambda} \end{pmatrix} = \boldsymbol{J}_{\mathrm{RCM}}(\boldsymbol{q}, \lambda) \begin{pmatrix} \dot{\boldsymbol{q}} \\ \dot{\lambda} \end{pmatrix} = \boldsymbol{0}$$

pdot=J(q)*qdot

Jacobian of Pi

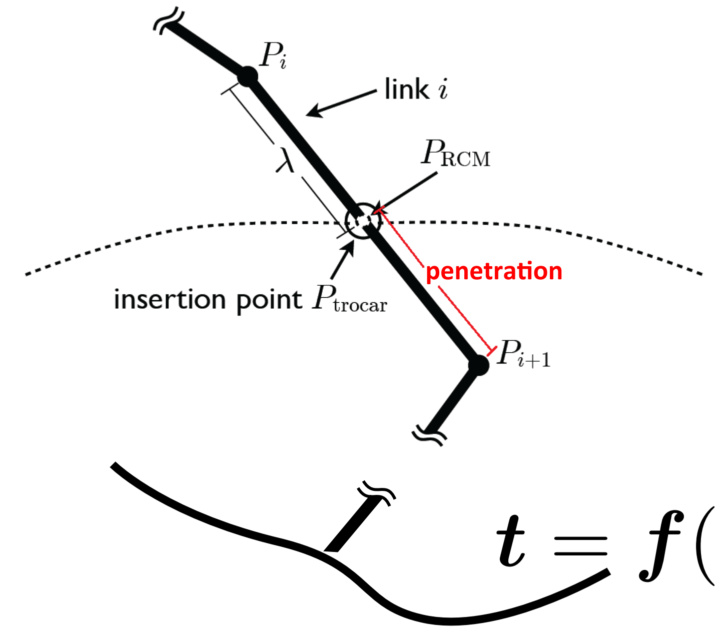
Moreover we want that the pRCM dot is equal to tthe velocity of Ptrocar that has no velocity, so pRCM dot is equal to zero

with $\boldsymbol{q} = (q_1 \ldots q_n)^T$ vector of joint variables

$\boldsymbol{p}_i(\boldsymbol{q}(t)), \boldsymbol{p}_{i+1}(\boldsymbol{q}(t))$ cartesian coordinates of points P_i, P_{i+1}

With this model we define what we want the dobot does(we control the robot at the kinematic level). For ex. we want the robot execute a given task like follow a trajectory inside the body while satisfying the remote center of motion constraint

task control



$$\boldsymbol{t} = \boldsymbol{f}(\boldsymbol{q})$$

we define a task in the cartesian space

$$\dot{\boldsymbol{t}} = \boldsymbol{J}_t(\boldsymbol{q})\dot{\boldsymbol{q}} \qquad n_t \times n \text{ task jacobian}$$

we define also an extended task that is extended by adding the RCM constraint

define

$$\boldsymbol{J}$$

$$\dot{\boldsymbol{t}}_{\mathrm{EXT}} = \begin{pmatrix} \dot{\boldsymbol{t}} \\ \boldsymbol{0}_{3\times 1} \end{pmatrix} = \begin{pmatrix} \boldsymbol{J}_t & \boldsymbol{0}_{n_t\times 1} \\ \multicolumn{2}{c}{\boldsymbol{J}_{\mathrm{RCM}}} \end{pmatrix} \begin{pmatrix} \dot{\boldsymbol{q}} \\ \dot{\lambda} \end{pmatrix}$$

→ kinematic equation that describe the task as function of the joint velocity.

$$\boldsymbol{t}_{d,\mathrm{EXT}} = \begin{pmatrix} \boldsymbol{t}_d \\ \boldsymbol{p}_{\mathrm{trocar}} \end{pmatrix} \qquad \boldsymbol{e}_t = \begin{pmatrix} \boldsymbol{t}_d - \boldsymbol{t} \\ \boldsymbol{p}_{\mathrm{trocar}} - \boldsymbol{p}_{\mathrm{RCM}} \end{pmatrix}$$

If J is square, we can invert the matrix, but usually is not the case, then we need a redundant robot with respect to this extended task.

kinematic control, assuming $n > n_t + 2$

n:number of dof
nt:dim of the task
2:dim of the task constraint

If we have redundant dof, we can project an auxiliary velocity in the null space

feedback error

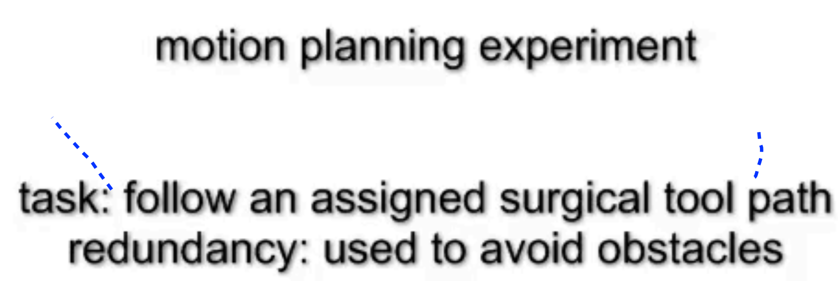
$$\begin{pmatrix} \dot{\boldsymbol{q}} \\ \dot{\lambda} \end{pmatrix} = \boldsymbol{J}^{\#}\dot{\boldsymbol{t}}_{d,\mathrm{EXT}} + \boldsymbol{J}^{\#}\begin{pmatrix} \boldsymbol{K}_t & \boldsymbol{0}_{\mathbf{n_t}\times\mathbf{3}} \\ \boldsymbol{0}_{\mathbf{3}\times\mathbf{n_t}} & \boldsymbol{K}_{\mathrm{RCM}} \end{pmatrix}\boldsymbol{e}_t + (\boldsymbol{I} - \boldsymbol{J}^{\#}\boldsymbol{J})\boldsymbol{w}$$

desired value of the velocity of the extended task

$$\boxed{\boldsymbol{J}^{\#} = \boldsymbol{J}^T(\boldsymbol{J}\boldsymbol{J}^T)^{-1}}$$

RCM constrained motion planning

task error $\quad \boldsymbol{e}_t = \begin{pmatrix} \boldsymbol{t}_d - \boldsymbol{t} \\ \boldsymbol{p}_{\mathrm{trocar}} - \boldsymbol{p}_{\mathrm{RCM}} \end{pmatrix}$ $\boldsymbol{t}$: surgical tool tip path



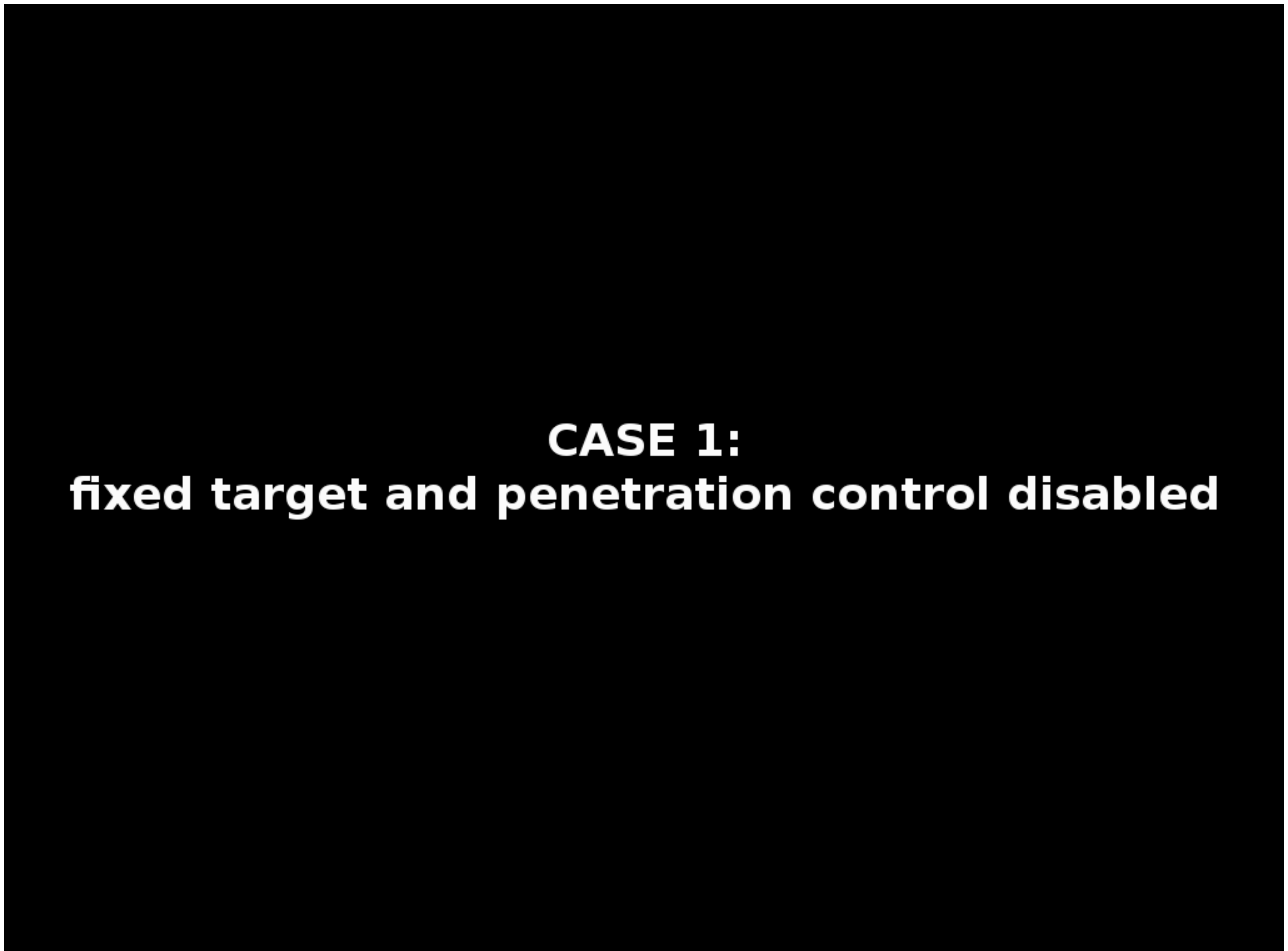
visual task

task error $e_t = \begin{pmatrix} \boldsymbol{f}_d - \boldsymbol{f} \\ \boldsymbol{p}_{\mathrm{trocar}} - \boldsymbol{p}_{\mathrm{RCM}} \end{pmatrix}$ $\boldsymbol{f}$: vector of visual features

the visual features are regulated while satisfying the RCM constraint and the penetration stays close to a desired value

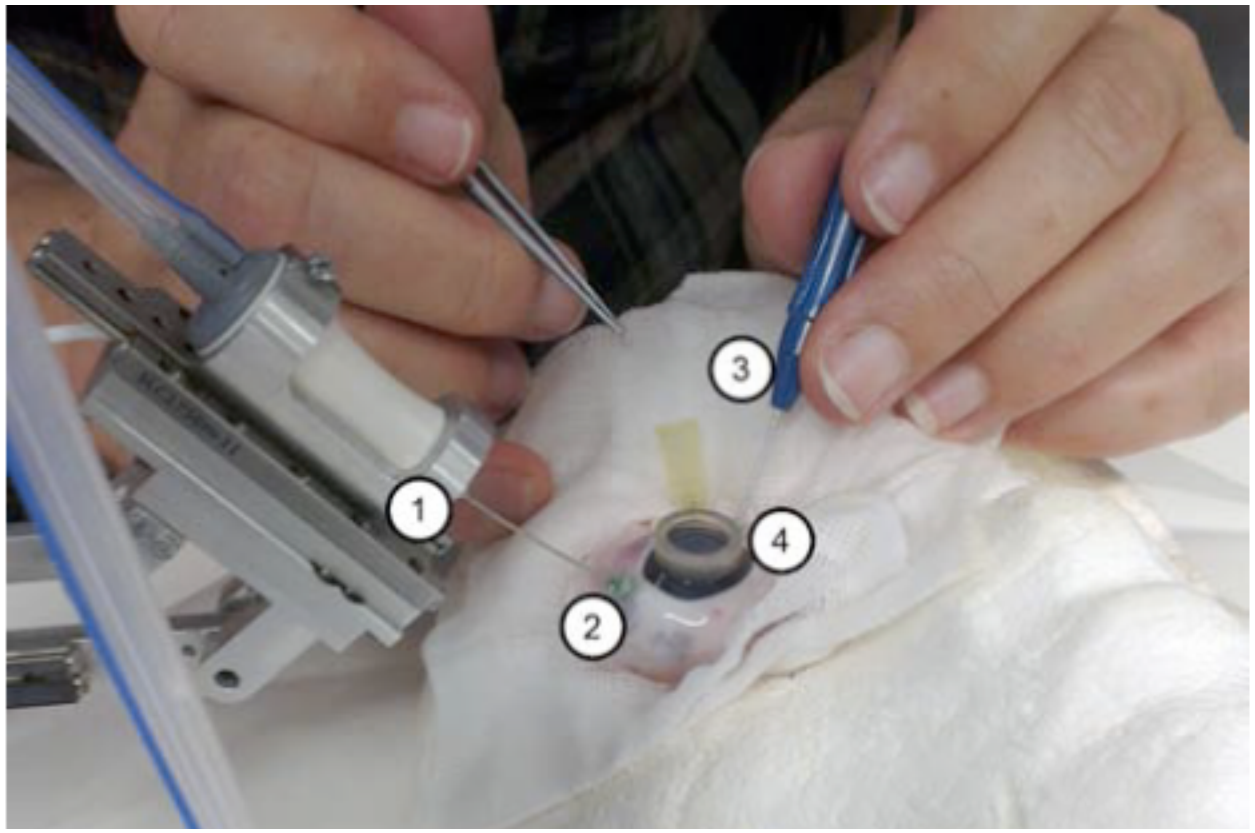
visual task

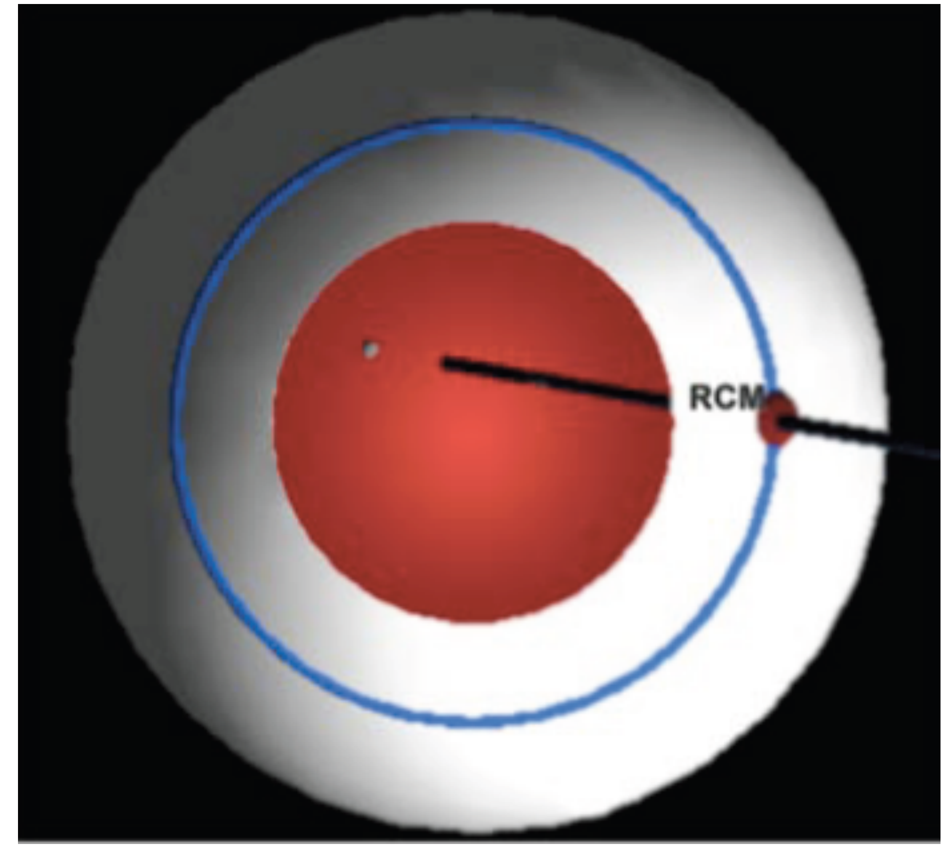
task error $$e_t = \begin{pmatrix} \boldsymbol{f}_d - \boldsymbol{f} \\ \boldsymbol{p}_{\mathrm{trocar}} - \boldsymbol{p}_{\mathrm{RCM}} \end{pmatrix}$$ $\boldsymbol{f}$: vector of visual features

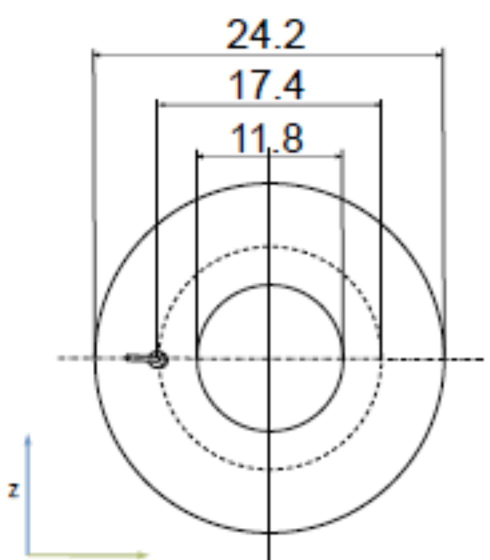


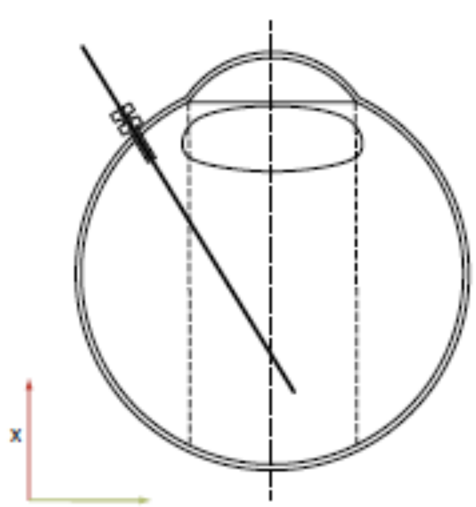
vitreo-retinal ophthalmologic surgery

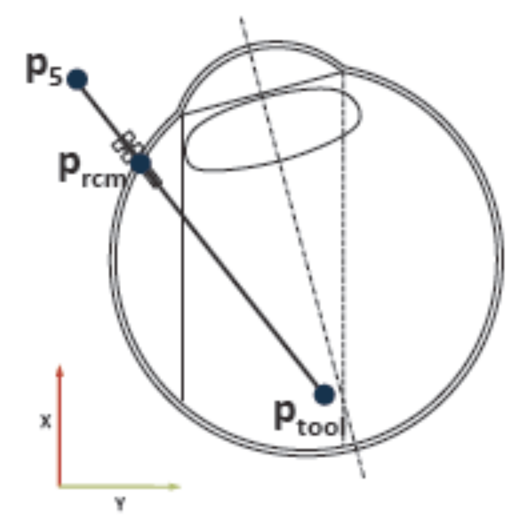
task: tool tip positioning

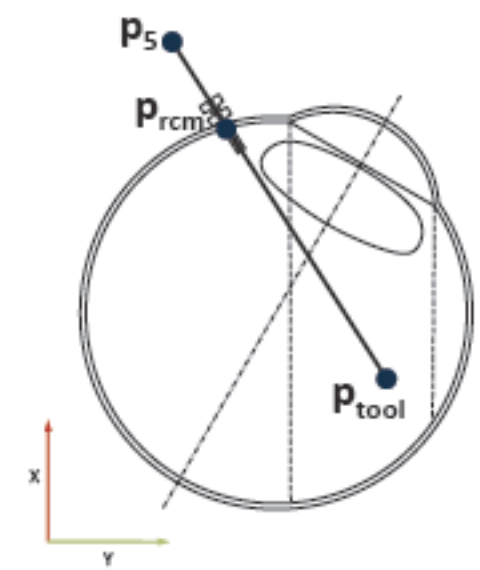










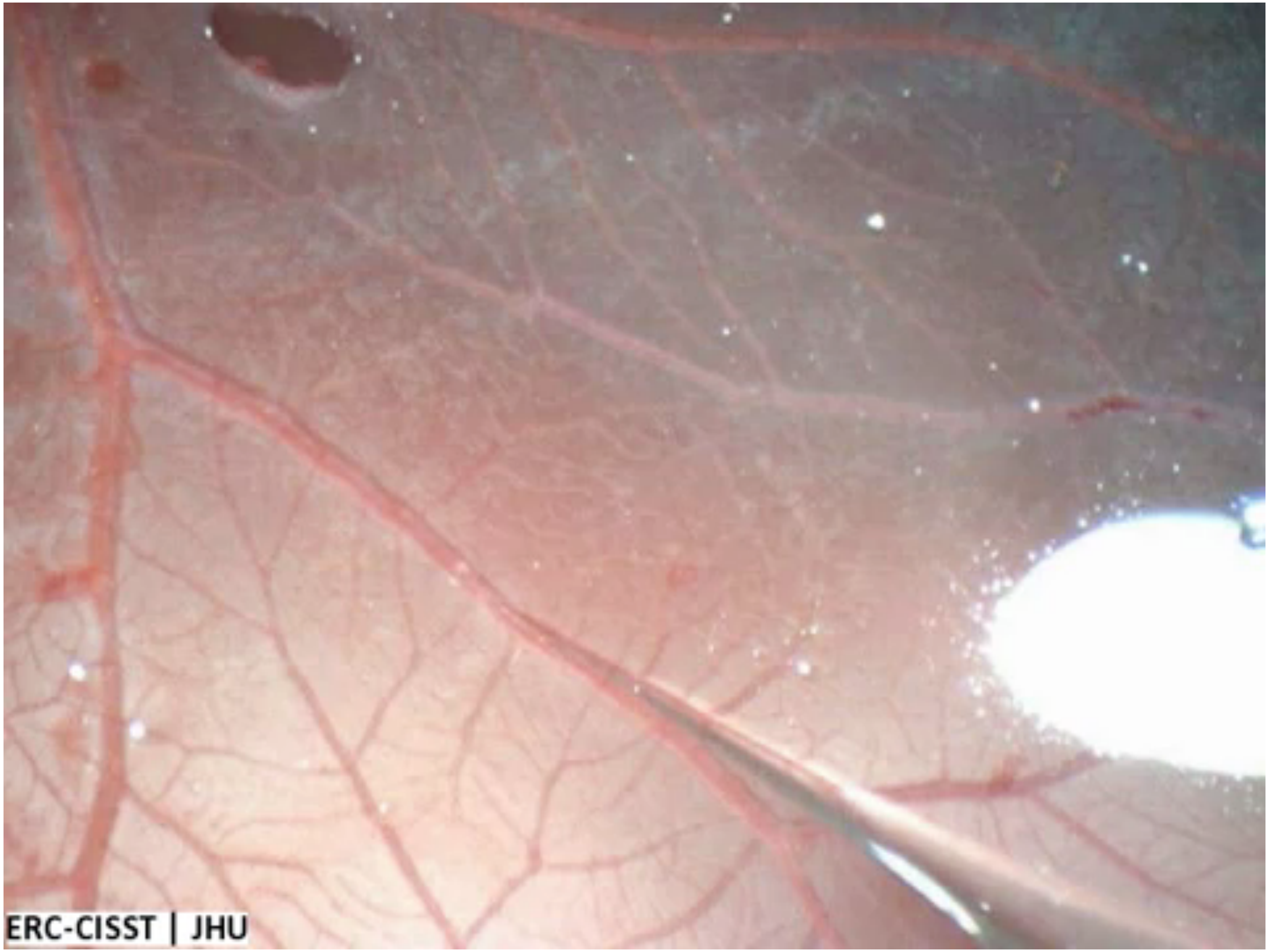


vitreo-retinal ophthalmologic surgery

task: tool tip positioning

vitreo-retinal ophthalmologic surgery

task: retinal vein cannulation https://ciis.lcsr.jhu.edu/dokuwiki/doku.php?id=research.eyerobots



virtual fixtures and RCM

given the curve in parametric form

$$p(s) \equiv [x(s), y(s), z(s)]^T$$

project the input force $\boldsymbol{f}$ on the tangent to the curve $p\prime$ in the point $\hat{s}$ closest to the current tool tip position

$$\boldsymbol{f}_t = \frac{\boldsymbol{p}'(\hat{s})^T \boldsymbol{f}}{||\boldsymbol{p}'(\hat{s})||^2} \boldsymbol{p}'(\hat{s})$$

virtual fixtures and RCM

preferred direction (taking into account the initial position error)

$$\boldsymbol{f}_\delta = \boldsymbol{f}_t + k_p \boldsymbol{e}(\hat{s})$$

desired tool tip velocity

$$\dot{\boldsymbol{t}}_d = c[\boldsymbol{f}_\delta + c_\tau \boldsymbol{f}_\tau]$$

$\boldsymbol{t}_d$ is obtained by integration with appropriate initial condition

kinematic control law

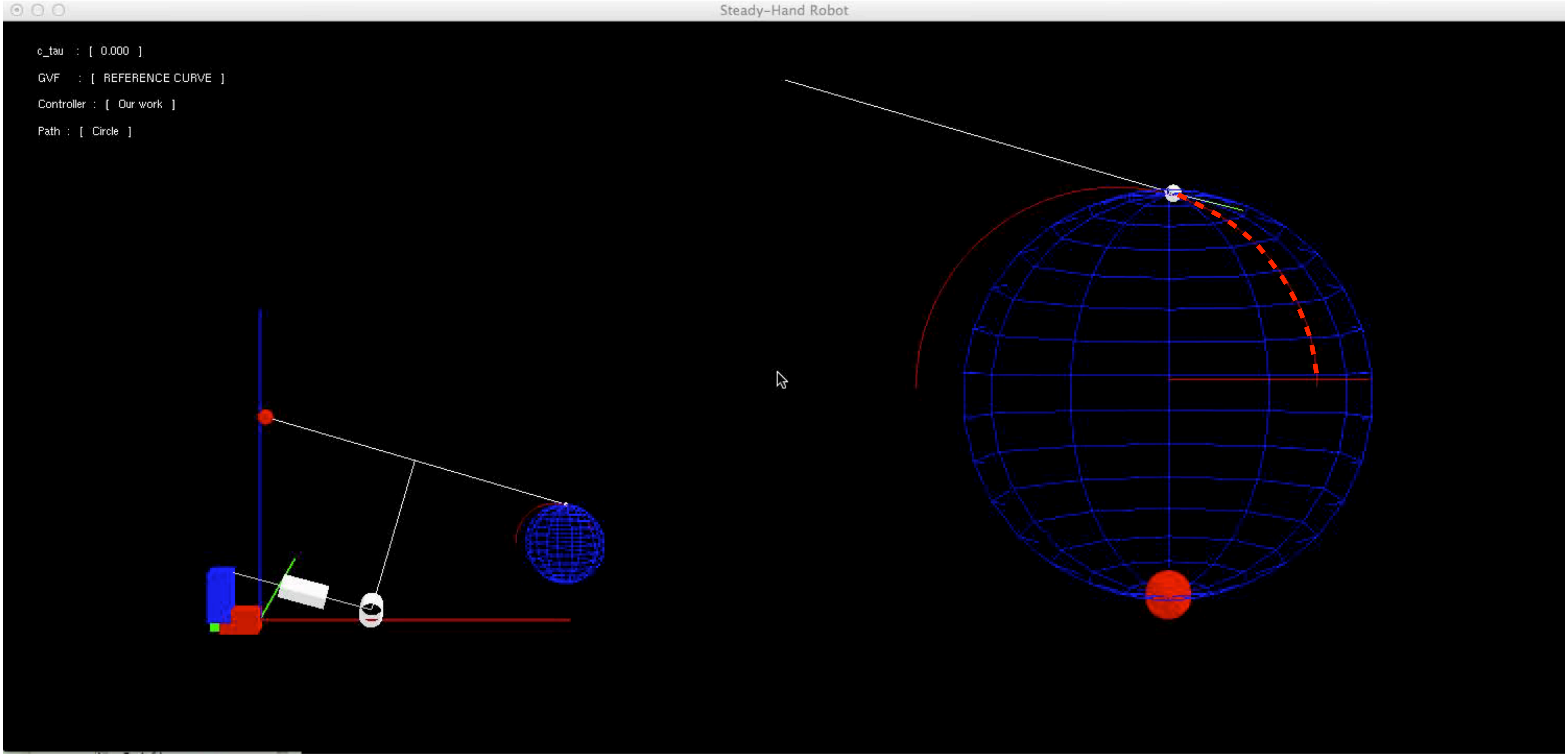
$$\begin{pmatrix} \dot{\boldsymbol{q}} \\ \dot{\lambda} \end{pmatrix} = \boldsymbol{J}^{\#} \dot{\boldsymbol{t}}_{d,\mathrm{EXT}} + \boldsymbol{J}^{\#} \begin{pmatrix} \boldsymbol{K}_t & \mathbf{0}_{\mathbf{n_t} \times \mathbf{3}} \\ \mathbf{0}_{\mathbf{3} \times \mathbf{n_t}} & \boldsymbol{K}_{\mathrm{RCM}} \end{pmatrix} \boldsymbol{e}_t + (\boldsymbol{I} - \boldsymbol{J}^{\#} \boldsymbol{J}) \boldsymbol{w}$$

with

$$\boldsymbol{e}_t = \begin{pmatrix} \boldsymbol{t}_d - \boldsymbol{t} \\ \boldsymbol{p}_{\mathrm{trocar}} - \boldsymbol{p}_{\mathrm{RCM}} \end{pmatrix}$$

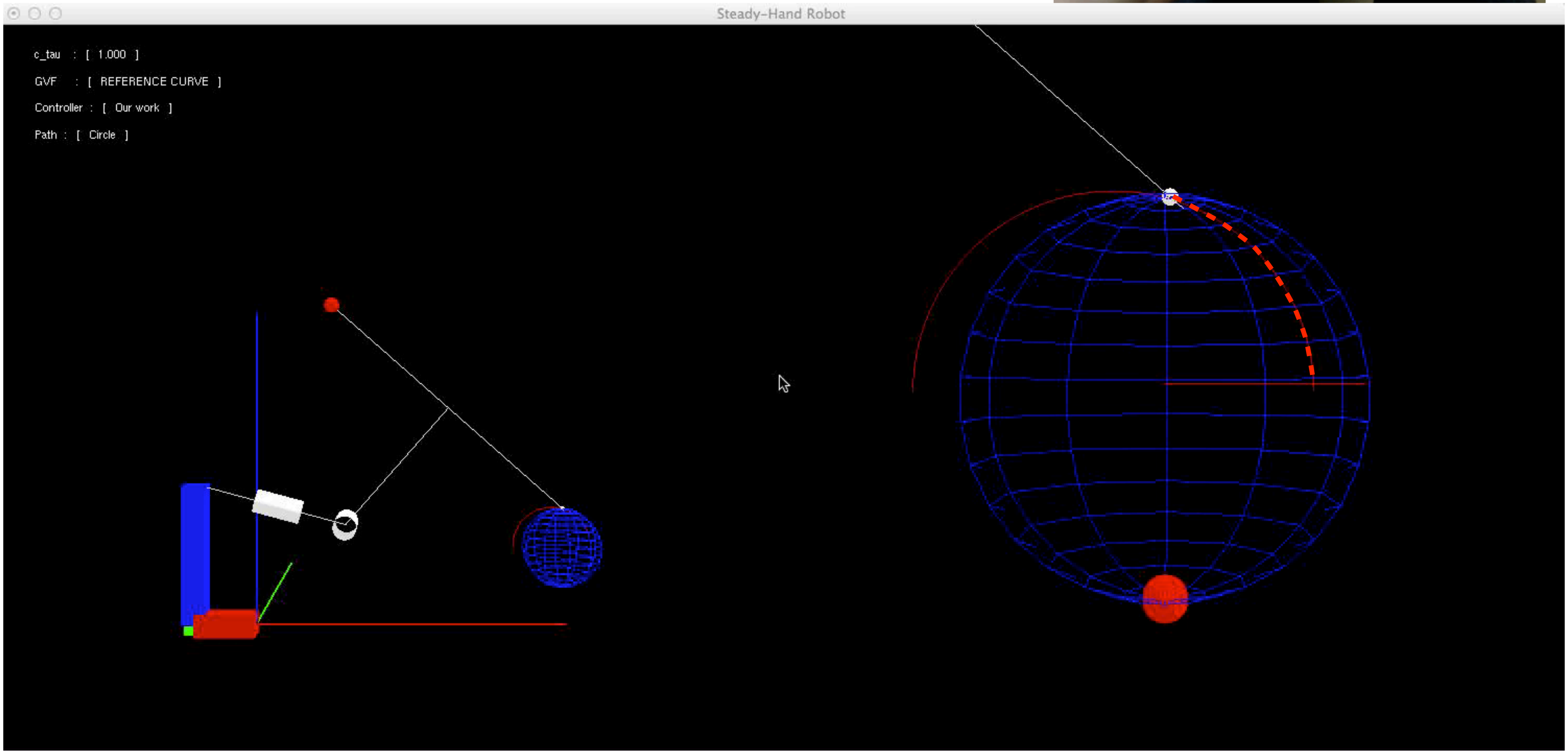
virtual fixtures and RCM

$c_\tau = 0$, GVF = first curve, then target



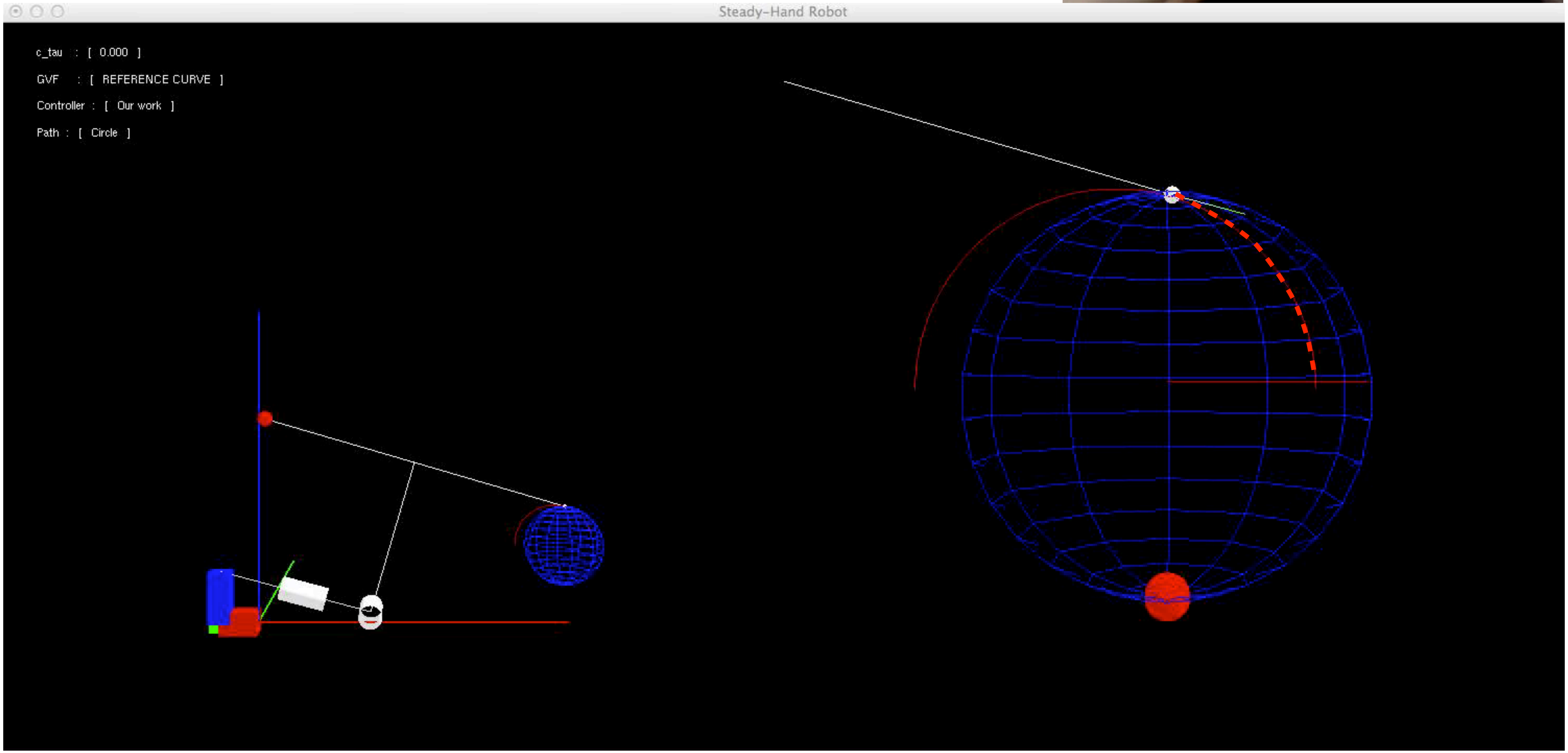
virtual fixtures and RCM

$c_\tau = 1$, GVF = curve following



virtual fixtures and RCM

increasing c_τ



References

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- M. A. Nasseri, P. Gschirr1, M. Eder, S. Nair, K. Kobuch, M. Maier, D. Zapp, C. Lohmann, A. Knoll, “Virtual Fixture Control of a Hybrid Parallel-Serial Robot for Assisting Ophthalmic Surgery: an Experimental Study,” 2014 5th IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechatronics (BioRob)