Medical Robotics

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Kinematic Design of Medical Robots

(part II: less conventional architectures and examples)

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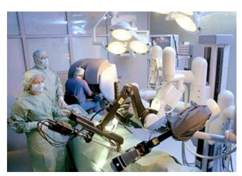
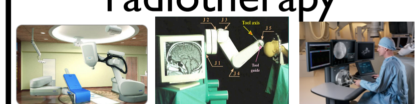
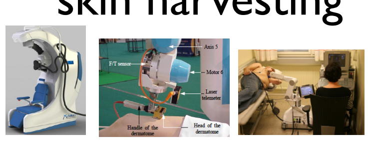
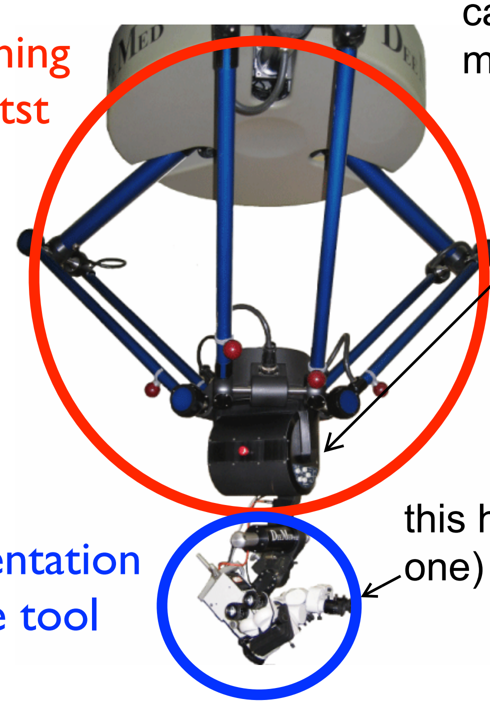
what we have seen so far

domain of use	function	kinematic architecture	control modality	sensors and actuators
orthopedics 	machining of rigid surface	**conventional** 5 (drill) or 6 (cut) dof	autonomous cooperative or “hands-on”	conventional vel: mm/s force: until 100N
MIS 	constrained manipulation	**RCM** 5 or 6 external + extra internal dof	teleoperation shared control	conventional vel: cm/sec (high acceleration in case of beating hearth surg) force: few N
neurosurgery, int. radiology, radiotherapy 	constrained targeting	**conventional + front-end with dedicated architecture**	teleoperation (semi)-autonomous	MR/CT compatible (pneumatic, ultrasonic) force: few N insertion (usually) manual (undetermined in case of neurosurgery)
microsurgery 	micromanipulation	**dedicated kinematic architecture**	shared/cooperative teleoperation	piezo, ultrasonic actuators force: few mN vel: 0.70m/s (manual procedure)
tele-echo, TMS, skin harvesting 	surface tracking	**conventional + dedicated wrist architecture**	autonomous teleoperation	conventional vel: mm/s force: few N

less “conventional” kinematic structures

we have 3 arms that are all connected to the same rigid object that you can see as an E-E. This is used for positioning the tool like endoscope, microspcope...



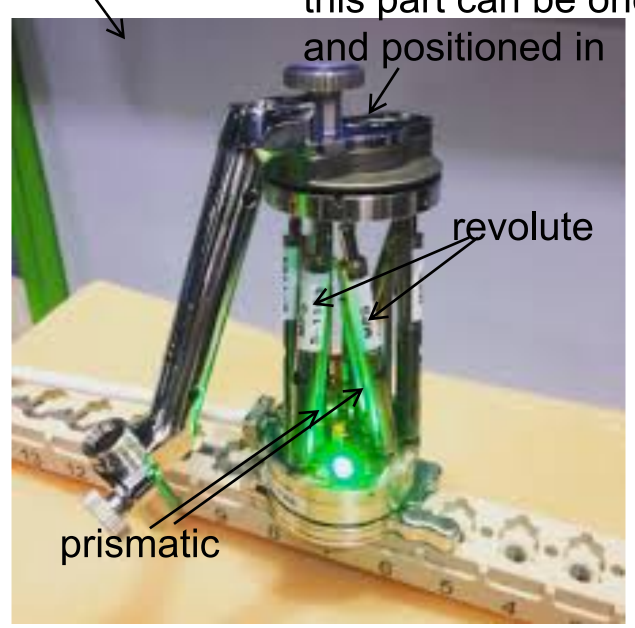
- holding and positioning of tools (endoscopes, biopsy needles, electrodes) during neurosurgery

this hibrid structure (parallel linkage following by a serial one) is very popular ir medical robotics

2 prismatic joints instead of one stabilize the structure

Inside this robot we have similar structure of below. We have prismatic joints and revolute joints; not all are active but many are

- parallel architecture with 6 dof (Stewart platform) for spinal surgery
- sterilizable, size: 50X50X80 mm^3, weight: 250 gr, workspace volume: 20X20X20 mm^3
- accuracy of positioning of the surgical tool < 0.1 mm



Renaissance

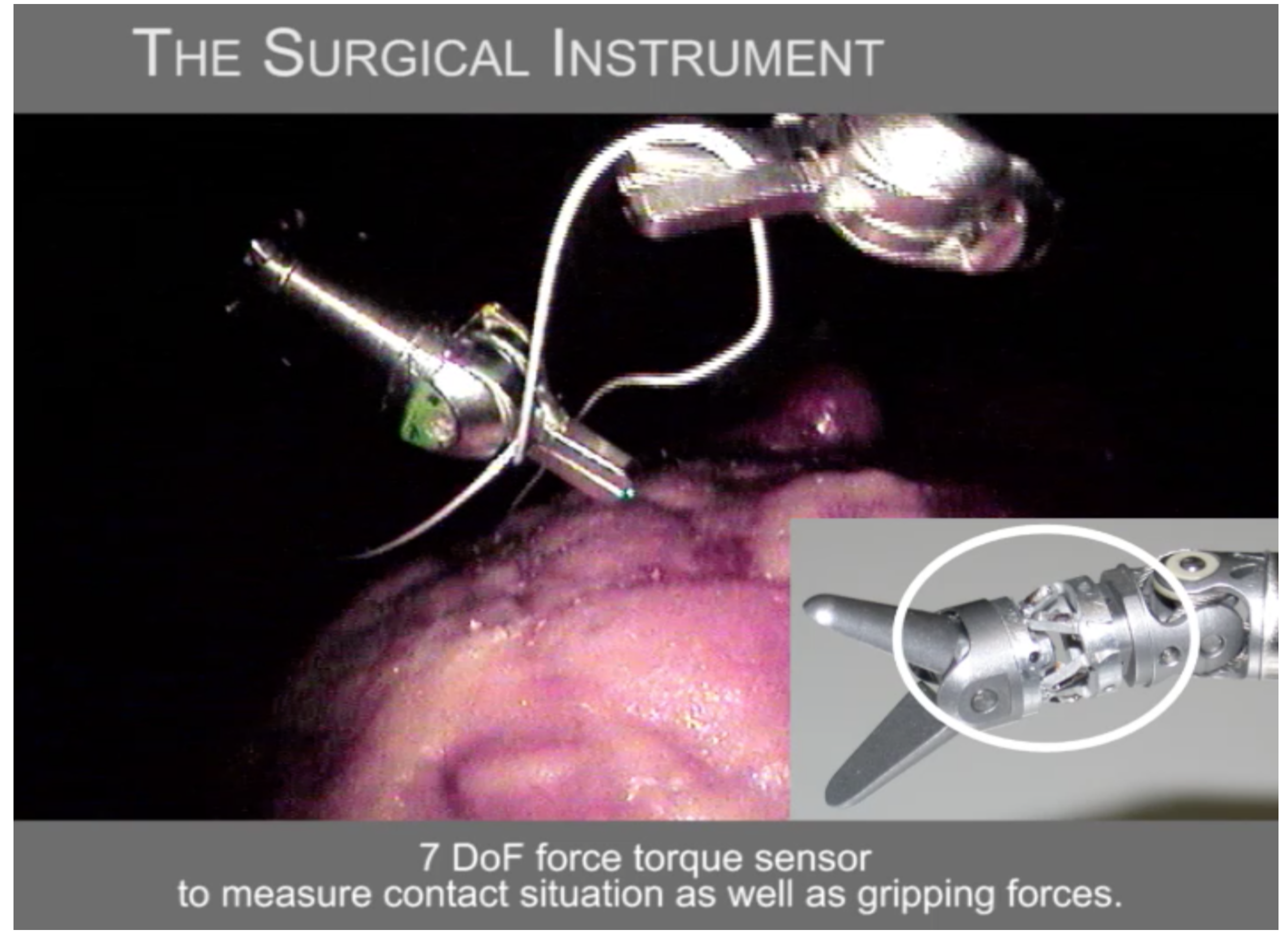
seen in the initial slides

https://www.youtube.com/watch?v=3eJCBAUcIMQ

XACT Robotics (technology similar to Reinassance)

different workspace size, different use

parallel wrists for mini-manipulators (CERT and INRIA)



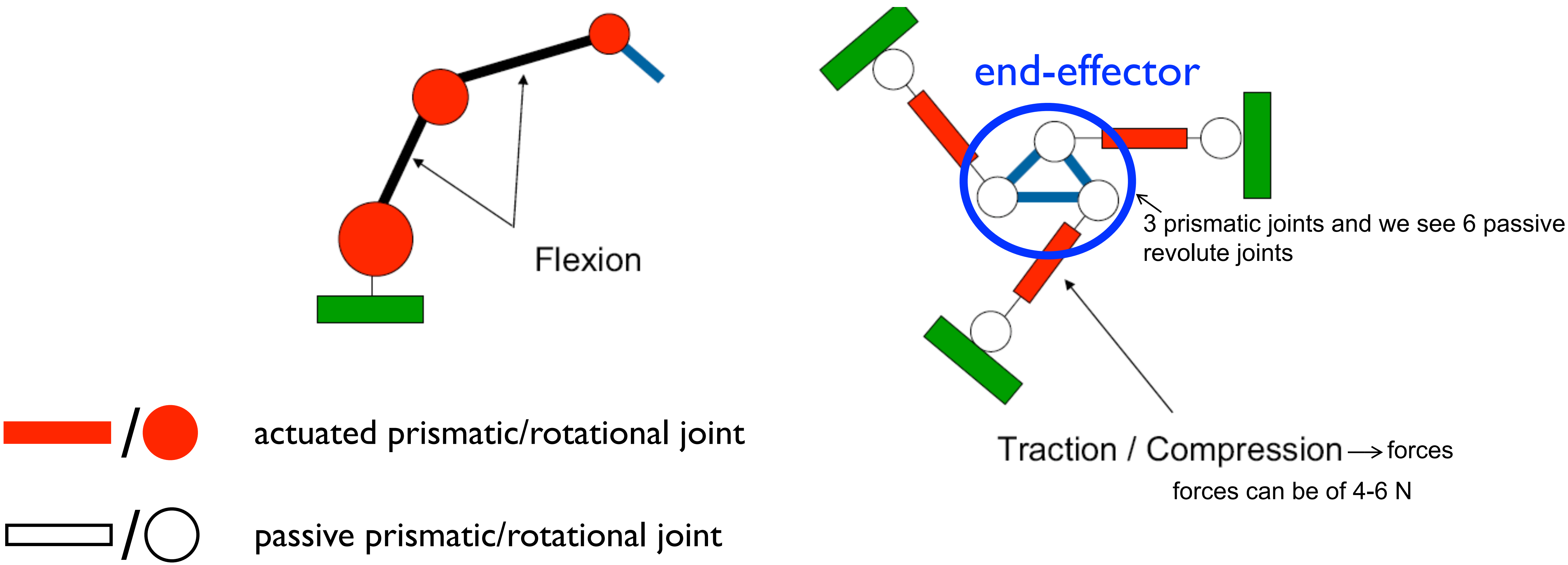
force sensor (MIRO, DLR)

master station equipped with a parallel arm structure
(Force Dimension) seen in the introductory lesson for vascular procedure

← It is teleoperated. All joints are connected to the same E-E.

parallel architectures: advantages
(with respect to a serial architecture)

The first is that, if yyou have quite long link these are subjected to a flection, so we have a deformatio of the structure that reduces the accuracy and sometimes also stability of motion. With a parallel architecture the structure is more rigid.

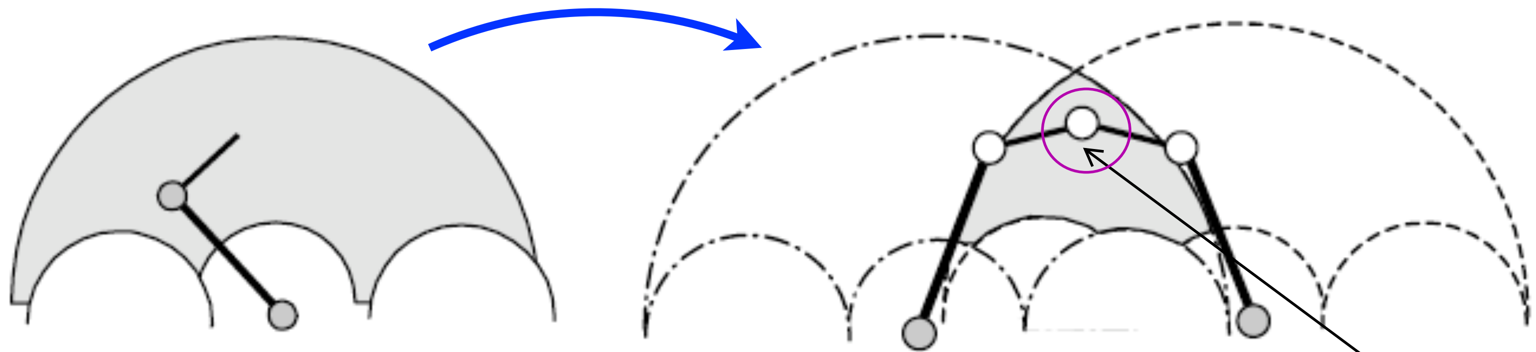


- stiffness, accuracy, speed, acceleration (up to 40 g!)
- good weight/load ratio

parallel architectures: drawbacks

one of the main drawback is that related to the workspace

two serial chains "closed"
at the end-effector



serial 2 arm manipulator

2 manipulators with 2-dof. This point can be moved in the plane but only within this reduced portion

they are not necessary for motion and they passively adapt to the motion

- a lot of passive joints

To allow motion the 3 joints (white circle) need to be passive

- direct kinematics not always in closed form

the closed form actuate all the joints but then they all need to be controlled in accurate and coordinated way, otherwise internal forces will be generated in way that they demage the traction

- non-classical calibration
- the foot-print/workspace ratio is generally considered to be bad but for some medical applications a ws comparable with the robot size is an advantage

in industrial or service robotics but in medical robotics is acceptable

parallel architectures: definitions

- **generalized parallel manipulator:** closed kinematic chain with the end-effector connected to the base through several independent kinematic chains

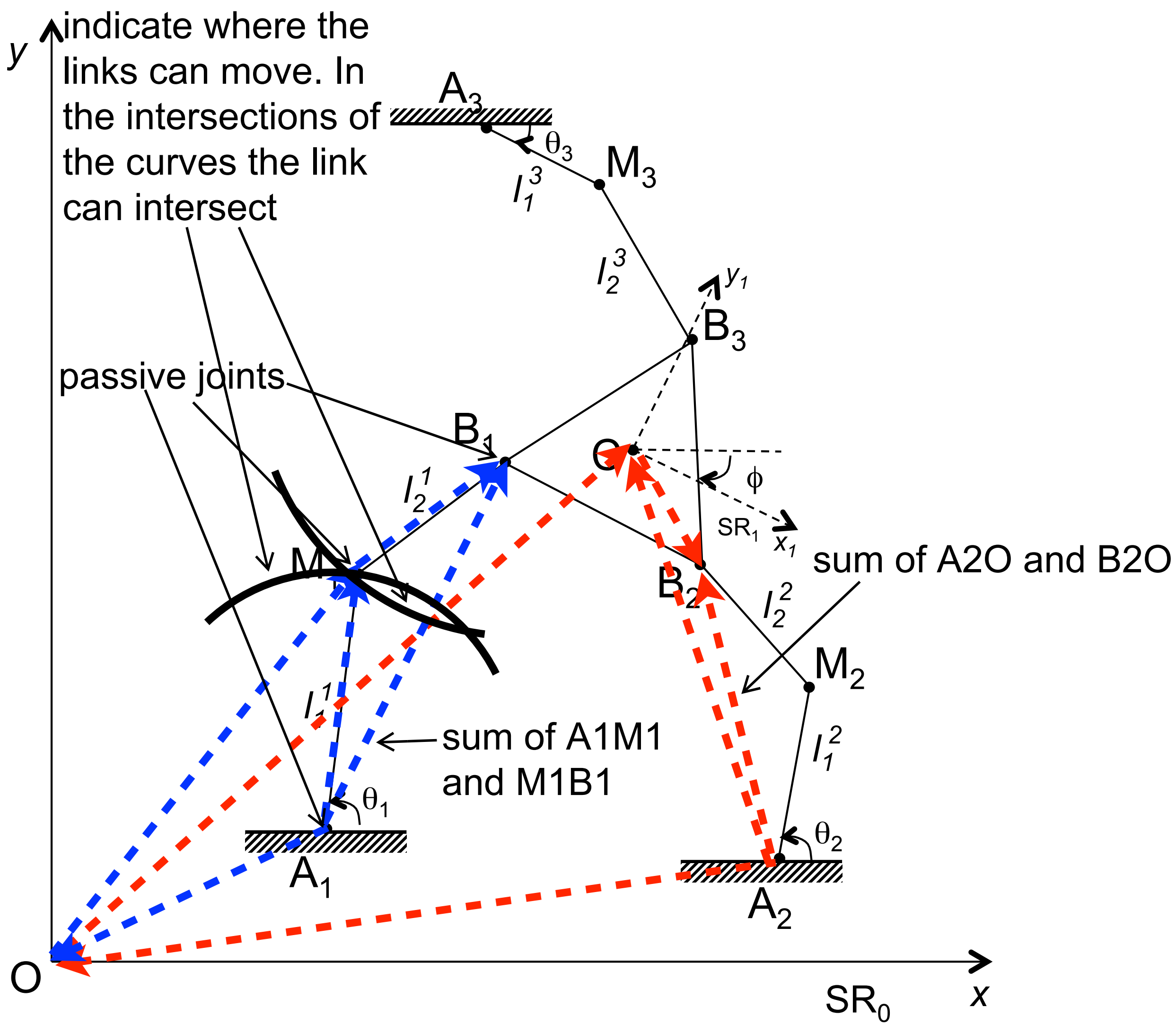
- **parallel robot:** formed by an end-effector with n dof and a fixed base connected by at least two independent kinematic chains and equipped with n actuators
  with the E-E

- **completely parallel manipulator:** parallel robots with a number of chains equal to the dofs of the end-effector

- parallel robots may be equipped by revolute, prismatic, universal (2 dof) or spherical (3 dof) joints

Why there are 8 solutions instead of 6? Because each of the 2 solutions for each lengths combines with other ones and so we have 2-2-2 combination of solutions

inverse kinematics of a planar parallel manipulator 3-RRR



problem: given the coordinates of point C and the angle ϕ, determine θ_1, θ_2, θ_3

known: A_i in SR_0, B_i in SR_1

$$\boxed{A_iB_i = A_iO + OC + {}^0R_1\,{}^1CB_i \qquad (1)}$$

${}^1CB_i$: coordinates of B_i in SR_1

$$\boxed{A_iB_i = A_iO + OM_i(\theta_i) + l_2^i n \qquad (2)}$$

n: unitary vector

(1) depends only on C and ϕ, (2) is a function of θ_i

from (1)= (2) one obtains

$$A_iO+OC+{}^0R_1\,{}^1CB_i = A_iO+OM_i(\theta_i)+l_2^i n \qquad (3)$$

from which it is possible to determine θ_i

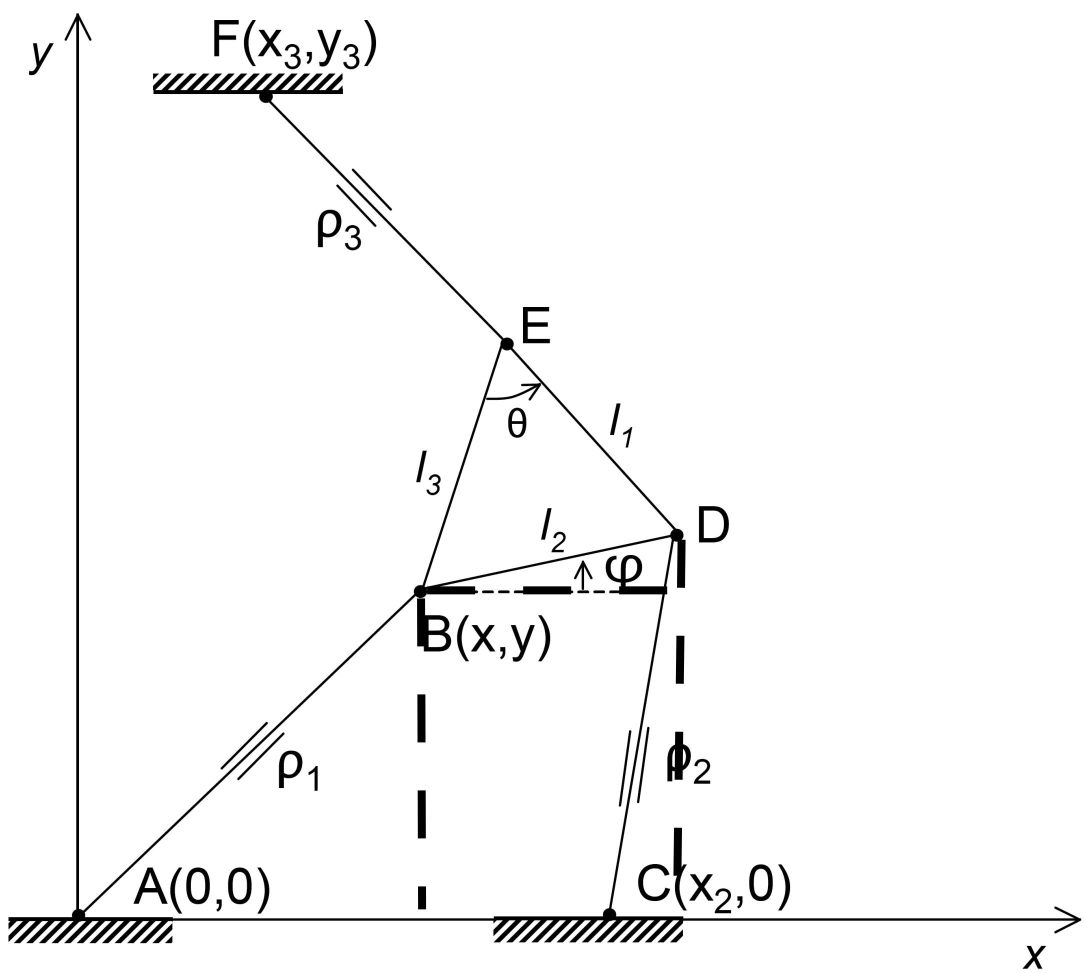
how many solutions? solving (3) corresponds to determine the coordinates of the points M_i lying at the intersections between the circles of ray l_1^i and l_2^i and center in A_i and B_i respectively $\Rightarrow$ 2 solutions for each kinematic chain, 8 solutions for the manipulator

remark 1: in this case the inverse kinematics can also be determined by observing that each of the three kinematic chain from the base to the end-effector (i.e., from A_i to B_i) is a 2R serial planar manipulator with known inverse kinematic; the methods here used is general and can be applied to different kinematic structures

remark 2: by determining θ_i it is possible to determine the values of the passive joints

direct kinematics of planar parallel manipulator 3-RPR

no obtained in closed form



2 rotational(passive) and 2 prismatic(active) joints

problem: given $\rho_1,\ \rho_2,\ \rho_3,$ determine the coordinates of B and the angle φ lenghts of the legs

known: A, C, F, θ, l_1, l_2, l_3

inverse kinematics:

$$\begin{aligned}\rho_1^2 &= x^2+y^2 \\ \rho_2^2 &= (x+l_2\mathsf{c}_\varphi-x_2)^2+(y+l_2\mathsf{s}_\varphi)^2 \\ \rho_3^2 &= (x+l_3\mathsf{c}_{\varphi+\theta}-x_3)^2+(y+l_3\mathsf{s}_{\varphi+\theta}-y_3)^2\end{aligned} \qquad (4)$$

$$\Downarrow$$

$$\begin{aligned}\rho_2^2-\rho_1^2 &= Rx+Sy+Q \\ \rho_3^2-\rho_1^2 &= Ux+Vy+W\end{aligned}$$

$$\Downarrow$$

$$x=-\frac{SA_1-VA_2}{\Delta} \qquad y=\frac{RA_1-UA_2}{\Delta}$$

having set:

$R=2(l_2\mathsf{c}_\varphi-x_2)$, $S=2l_2\mathsf{s}_\varphi$, $Q=x_2^2+l_1-2l_2\mathsf{c}_\varphi x_2$, $U=2(l_3\mathsf{c}_{\varphi+\theta}-x_3)$, $V=2(l_3\mathsf{s}_{\varphi+\theta}-y_3)$, $W=x_3^2+y_3^2+l_3-2l_3(x_3\mathsf{c}_{\varphi+\theta}+y_3\mathsf{s}_{\varphi+\theta})$, $A_1=\rho_3^2-\rho_1^2-W$, $A_2=\rho_2^2-\rho_1^2-Q$, $\Delta=RV-SU$

by substituting the expressions of x and y in (4) one obtains: this equation has only 1 unknown that is fi

$$(SA_1-VA_2)^2+(RA_1-UA_2)^2-\rho_1^2(RV-SU)^2=0 \qquad (5)$$

using the substitution $T=\tan\frac{\varphi}{2}$, $\cos\varphi=\frac{1-T^2}{1+T^2}$, $\sin\varphi=\frac{2T}{1+T^2}$, eq. (5) becomes

$$C_0+C_1T+C_2T^2+C_3T^3+C_4T^4+C_5T^5+C_6T^6=0$$

where the C_i's depend on the geometry of the manipulator

singular configurations

as shown by the previous examples, the relationships between the joint coordinates θ and the generalized coordinates X of the end-effector are expressed by

$$H_2(X, \theta) - H_1(X) = 0 \tag{6}$$

function of both E-E coordinates and the joints variable that depend on the E-E

differentiating (6)

$$U\dot{X} + V\dot{\theta} = 0 \tag{7}$$

which expresses the (linear) relationship between the joint velocities and the generalized velocity of the end-effector

there exists three possible singular cases $\longrightarrow$ depending on the rank of U and V matrices

- singular V: there exist $\dot{\theta}$ such that the platform does not move (correspond to poses on the frontier of the workspace)
- singular U: there exists $\dot{X}$ for which $\dot{\theta} = 0$; the corresponding poses form the set of singularities (also called *local* due to the infinitesimal movements of the structure when in these singular configurations)
- singular U and V: there exists a singular configuration such that the end-effector can move while the actuators are locked, and vice versa

singular configurations (cont'd)

singularities can also be characterized by studying the unicity of the solution of the direct kinematics in the neighborhood of a configuration

singular configurations correspond to the singularity of the inverse Jacobian matrix defined as the matrix which gives the relationship between the generalized coordinates of the e.-e. and the joint velocity

from a practical point of view, it is not easy to determine these singularities and the algebraic method can be used only for particular parallel robots

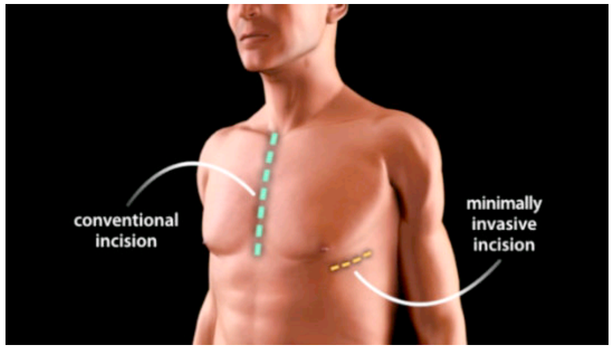
analogously to the serial manipulator, the existence of a duality velocity/force allows the characterization of singularities in terms of relationships between generalized forces F on the e.-e. and joint torques τ

– in correspondence of a singular configuration there not exist τ s.t. the system is at an equilibrium for a given F
– in the neighborhood of singular configurations the torques τ can be very high and the mechanical structure can be damaged

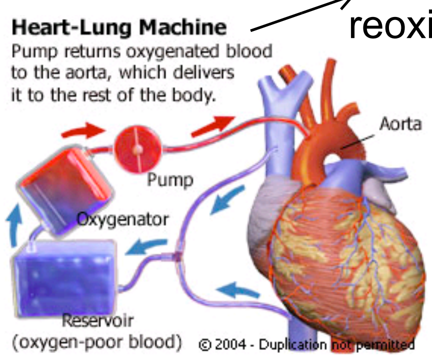
we can have a motion of the E-E also with zero velocity of the joints, but what is important is that also in proximity of the singuar points we can have high velocity close of the E-E in a singular point where the velocity of the joint is zero, closed to this singuarity we can have hogh velocity of the E-E for low velocity of the joints, so a sort of amplification

example 1: design of an active heart stabilizer

- traditional approach to cardiac surgery: the heart is stopped and an extracorporeal circulation (ECC) is activated

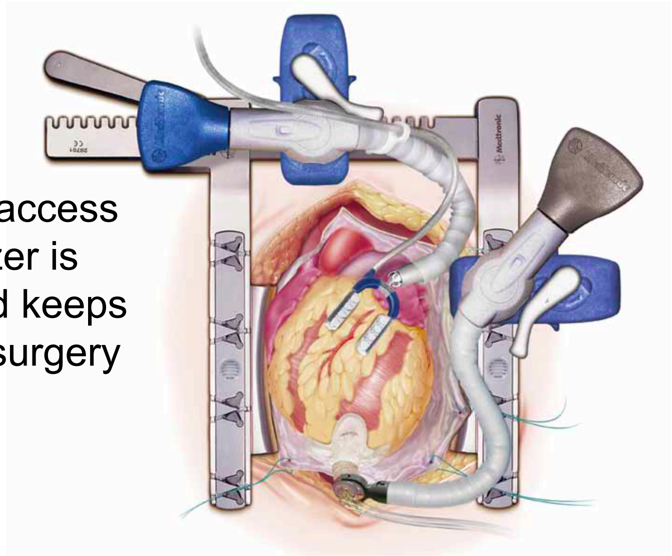


deviate the blood in an external circle, reoxigenation of blood



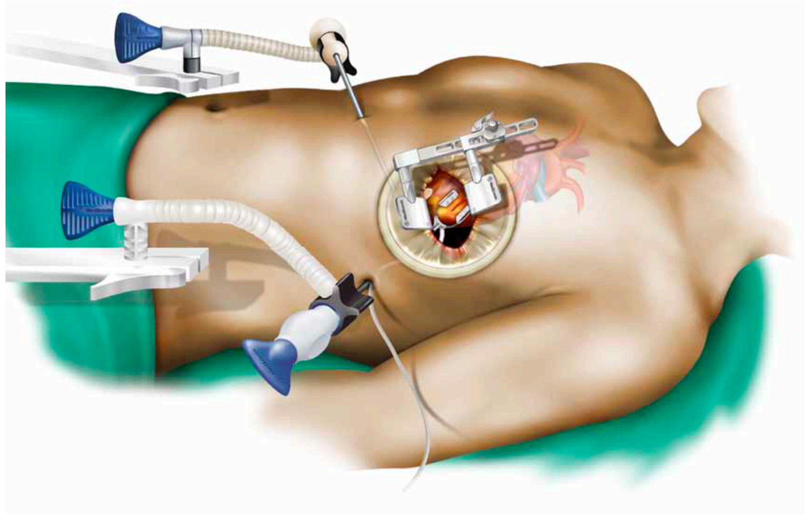
- beating heart surgery can avoid harmful effects of ECC (e.g., stroke, neurological impairment, vessel damage)
- a mechanical stabilizer is necessary to reduce the motion of the area interested by the procedure
- passive stabilizers exhibit residual motions of the order of mm
- the required precision is of the order of 0.1 mm

Once there is an open access to the heart, the stabilizer is placed on the heart and keeps the small area still the surgery is performed



this is open surgery

invasive stabilizer Octopus 4.3 (Medtronic)



endoscopic stabilizer Octopus TE (Medtronic)

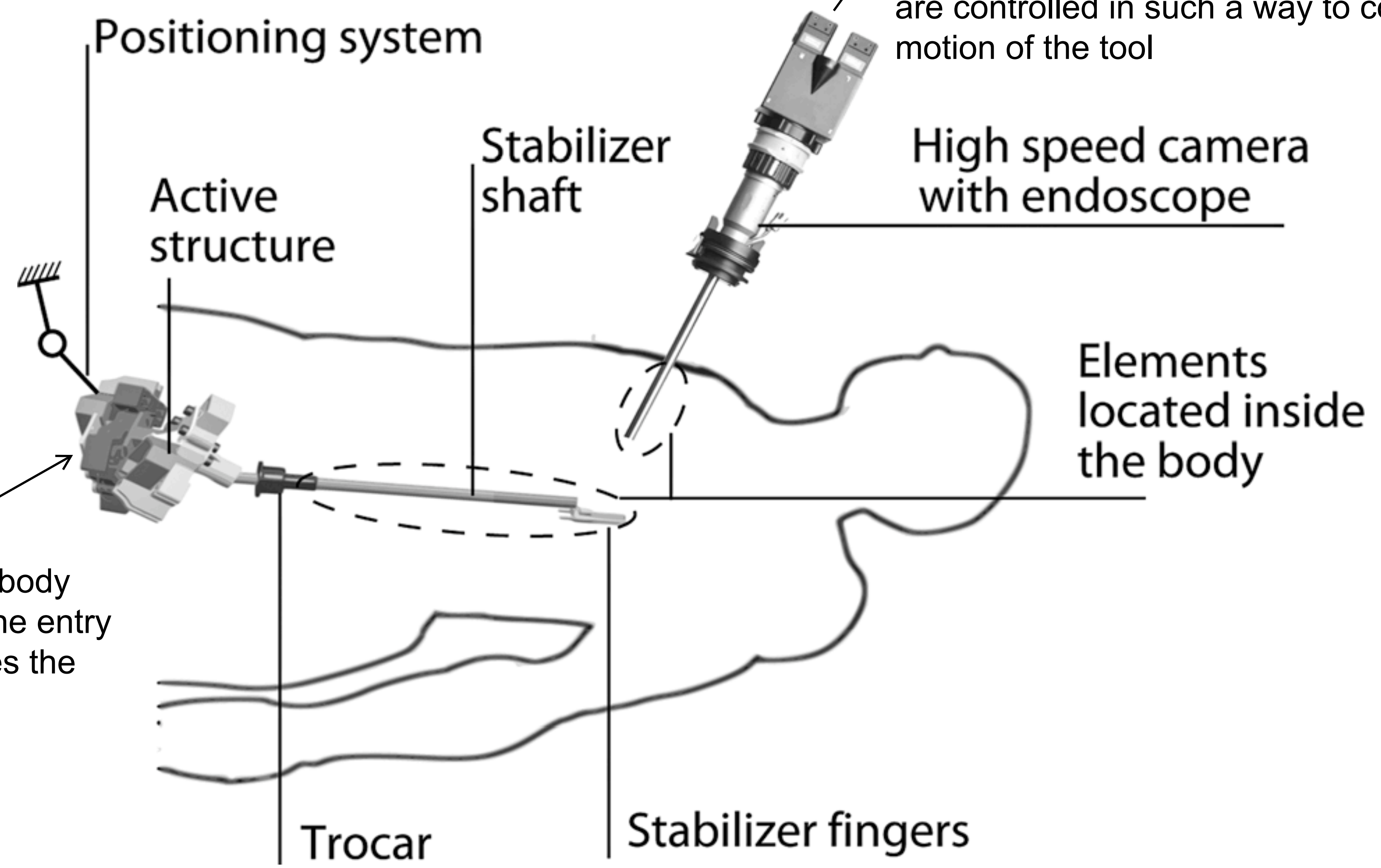
https://www.youtube.com/watch?v=YFtLM5LUnel

example 1: the Cardiolock active heart stabilizer

Instead of a passive stabilizer, we have an active stabilizer.

- the procedure is even more challenging if executed in a MIS context

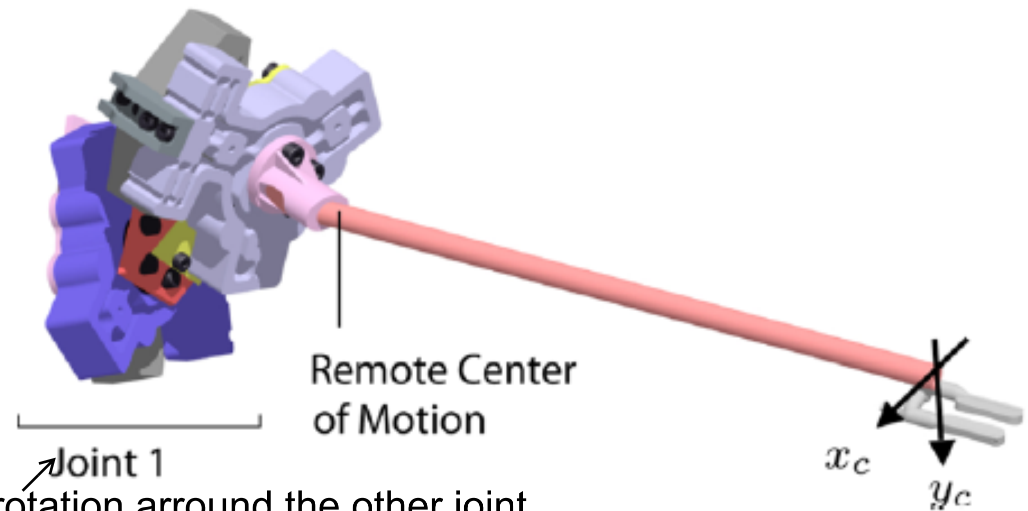
  ⇒ use an active stabilizer to compensate for heart motion



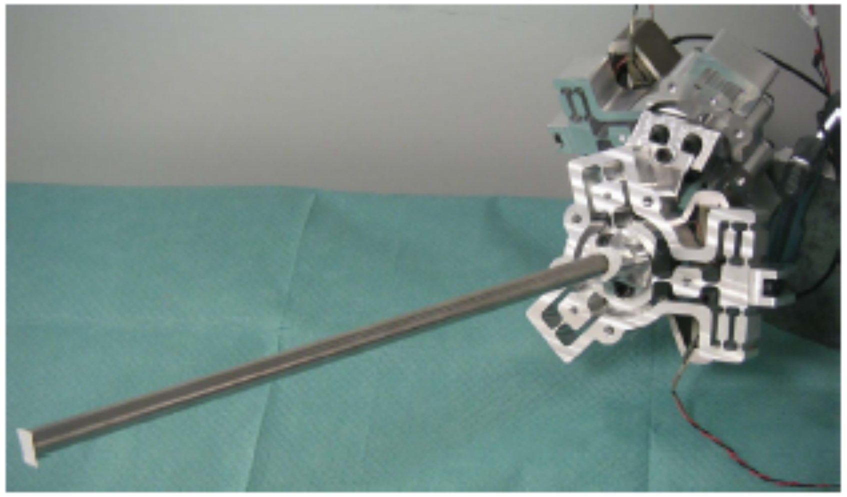
it detects the motion of the E-E(tip of the stabilizer) and according to the detective motion, the motors are controlled in such a way to compensate the motion of the tool

active stabilizer outside the body with 2 revolute joints. The stabilizer enters the body through a fixed point(RCM obtained at the entry point where trocar is placed) and reaches the right place.

example 1: the Cardiolock active heart stabilizer



provides rotation arround the other joint

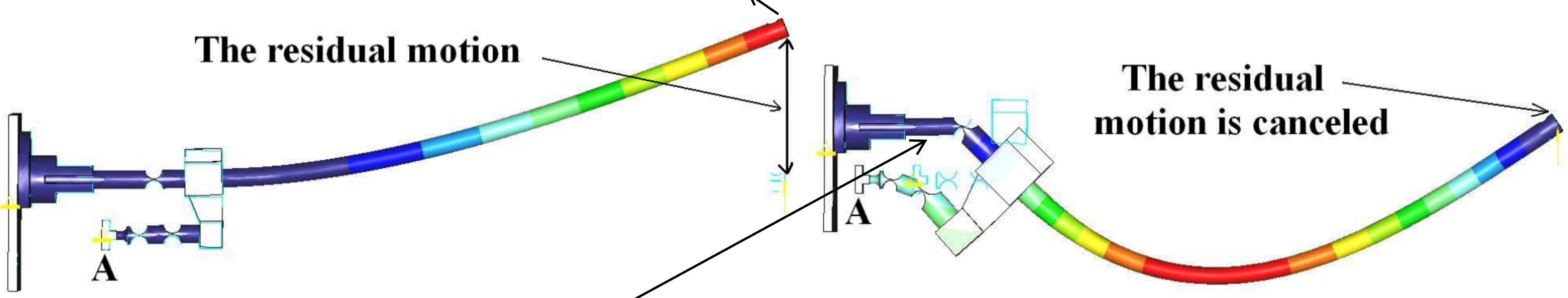


Cardiolock CAD model

Cardiolock prototype

the particularity of this model is in the 2 joints

tool tip

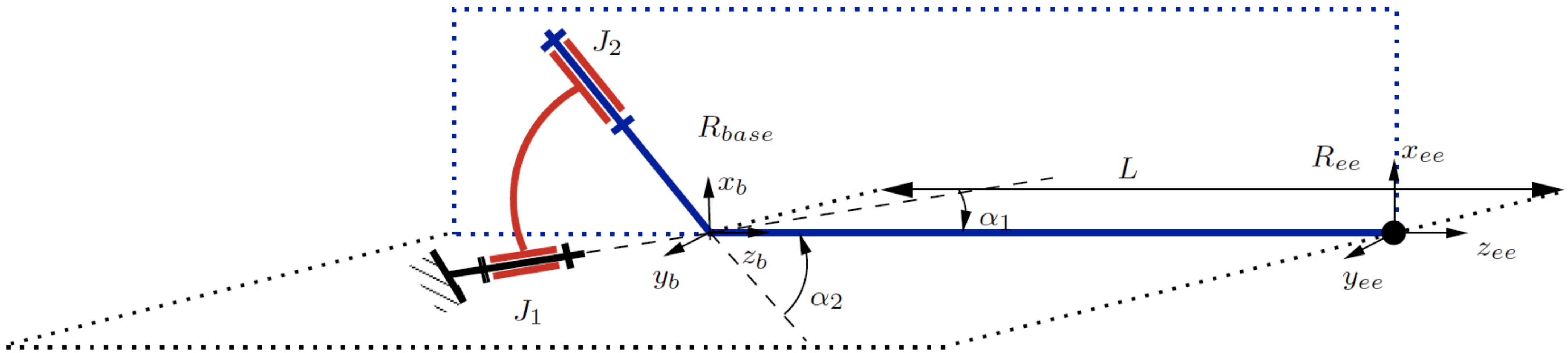


We assume there is a deformation only in one direction, if we have passive joints (that not actively compensate the motion), then we can have this deformation of the tool tip. To eliminate this residual motion, we use the principle of active compensation, so while a force is exacted here at the tool tip and there is a very very small motion, then here, the joint actively compensate that motion by a deformation.

finite elements analisys and principle of the compensation

example 1: design of an active heart stabilizer

active stabilizer kinematics



- two end-effector degrees of freedom in directions perpendicular to the stabilizer beam
- a RCM to limit the influence of the trocar forces
- the end-effector displacements needed to compensate for deflections are in the order of 1–2 mm $\Rightarrow L = 250$ mm (length of the stabilizer allowing a correct access to the area of interest) enables to approximate the needed device displacements by two rotations with respect to the RCM
- the rotations of the stabilizer beam are of small amplitude $\Rightarrow$ the special arrangement represented in the figure allows to get a decoupled behavior

example 1: design of an active heart stabilizer

jacobian matrix that relates the joint velocities $(\dot{\theta}_1 \; \dot{\theta}_2)^T$ to the end-effector velocities $(\dot{x}, \dot{y})$

$$\begin{pmatrix} \dot{x} \\ \dot{y} \end{pmatrix} = \begin{pmatrix} L\sin(\alpha_1) & 0 \\ 0 & L\sin(\alpha_2) \end{pmatrix} \begin{pmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \end{pmatrix}$$

- in principle, for a given set of end-effector displacements, the required displacements of the actuated joints decrease when angles α_1 and α_2 increase
- from a dynamical point-of-view, parameters α_1 and α_2 should be minimized in order to obtain a more compact structure, with lower inertias

slider crank: with this you can transformate linear motion in rotational motion

actuation of joints J_1 and J_2

- stack piezo actuators do not introduce any backlash or friction but deliver linear motion $\Rightarrow$ an actuation stage has to be designed in order to transform this motion in a rotation of the joints of the serial spherical architecture
- to lower the angles α_1 and α_2 a high ratio rotation/translation is needed
- a slider-crank mechanism does not allow to increase rotation/translation ratio without reducing stiffness in certain directions
- parallel architectures can provide at the same time a stiff structure, to minimize any uncontrollable displacements, and a large rotation from the displacement provided by the piezo actuator

example 1: design of an active heart stabilizer

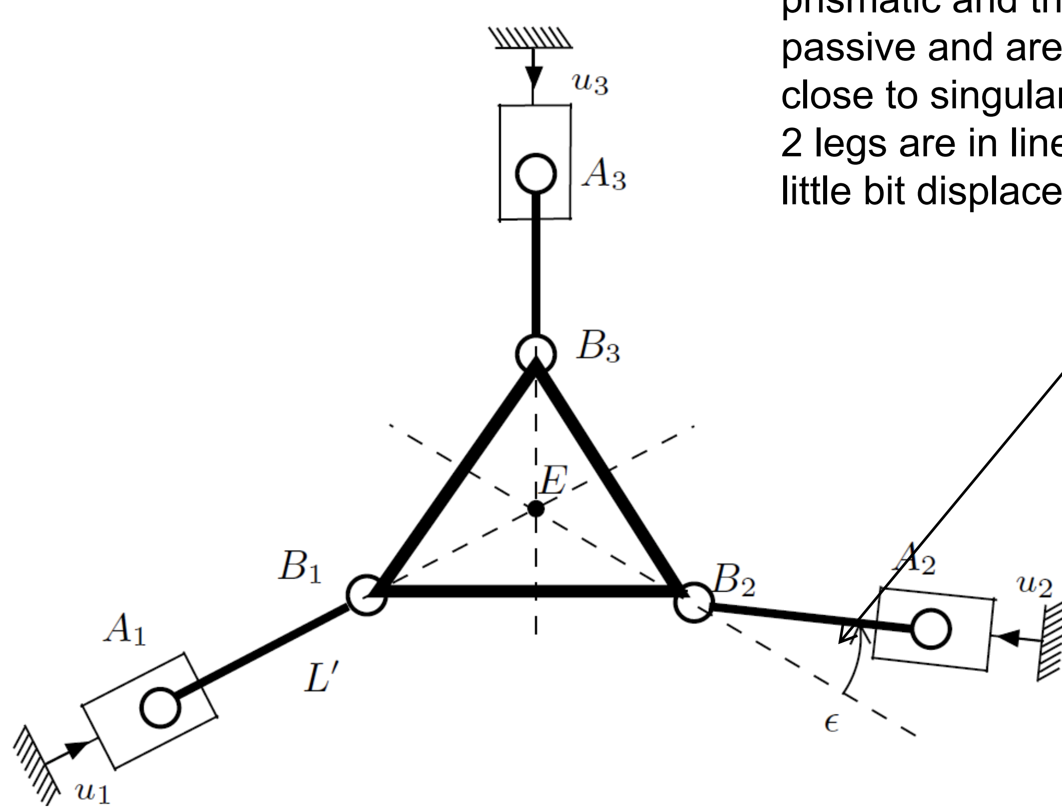
we have high E-E velocity for very small actuator velocity

relationship between actuator velocities $\dot{\mathbf{q}}$ and end-eff. velocities $\dot{\mathbf{X}}$ for a parallel mechanism

$$\mathbf{J_q}\,\dot{\mathbf{q}} = \mathbf{J_X}\,\dot{\mathbf{X}} \qquad (*)$$

- in a singularity, where $\mathbf{J_X}$ is not full rank, $\dot{\mathbf{X}} \neq \mathbf{0}$ can be obtained with $\dot{\mathbf{q}} = \mathbf{0}$
- in the vicinity of that singularity, one can tend to increase the ratio between actuators and end-effector velocities
- a 3-PRR in a configuration close to singularity provides the equivalent of a revolute joint; the thickness of this planar parallel structure can be selected to obtain the desired out-of-plane stiffnesses

we have 3-PRR manipulator, the first joint is prismatic and the only that is active, the other 2 are passive and are mounted in a configuration which is close to singularity. We have an equilateral triangle, 2 legs are in line with the bisector, but the third is a little bit displaced by an angle epsilon.



example 1: design of an active heart stabilizer

cartesian coordinates

- the pose of the end-effector $\mathbf{X} = (x, y, \theta)$ is determined by its orientation θ and by the position (x, y) of the point E

q1, q2 and q3 are the active joints variables

- the expression of $\mathbf{J_q}$ and $\mathbf{J_X}$ can be easily derived by noting that the velocities $\mathbf{v_{A_i}}$ and $\mathbf{v_{B_i}}$ of points A_i and B_i, respectively, satisfy the equality

$$\mathbf{v_{A_i}} \cdot \mathbf{A_iB_i} = \mathbf{v_{B_i}} \cdot \mathbf{A_iB_i}$$

  relating the velocities of any two points A_i and B_i of a rigid body (known as equiprojective peoperty)

- in this case $\mathbf{v_{A_i}} = \dot{q}_i \mathbf{u_i}$, $\mathbf{v_{B_i}} = \mathbf{v_{E_i}} + B_iE \times \dot{\theta}$, $(i = 1, 2, 3)$ which can be rewritten in the matrix form $(*)$, with

matrix that linearly depends on q dot.

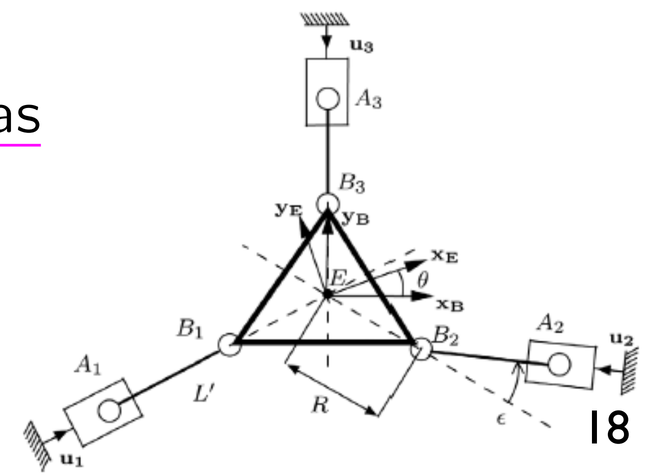
$$\mathbf{J_q} = \begin{pmatrix} \mathbf{u_1} \cdot \mathbf{A_1B_1} & 0 & 0 \\ 0 & \mathbf{u_2} \cdot \mathbf{A_2B_2} & 0 \\ 0 & 0 & \mathbf{u_3} \cdot \mathbf{A_3B_3} \end{pmatrix} \qquad \mathbf{J_X} = \begin{pmatrix} A_1B_1|_x & A_1B_1|_y & A_1B_1 \times B_1E|_\theta \\ A_2B_2|_x & A_2B_2|_y & A_2B_2 \times B_2E|_\theta \\ A_3B_3|_x & A_3B_3|_y & A_3B_3 \times B_3E|_\theta \end{pmatrix}$$

- if we consider zero velocities for the mechanism legs 1 and 3, the end-effector velocity $(\dot{x}, \dot{y})$ is zero

- the velocity $\dot{q}_2$ of the actuator 2 is linked to the rotational speed $\dot{\theta}$ as

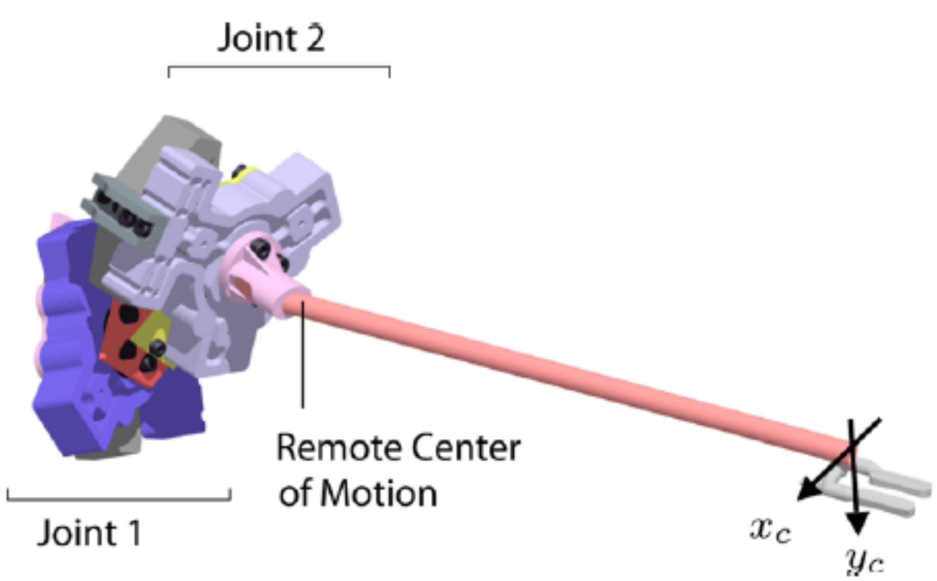
$$\dot{\theta} = \frac{1}{||EB_2|| \sin(\epsilon)} \dot{q}_2$$

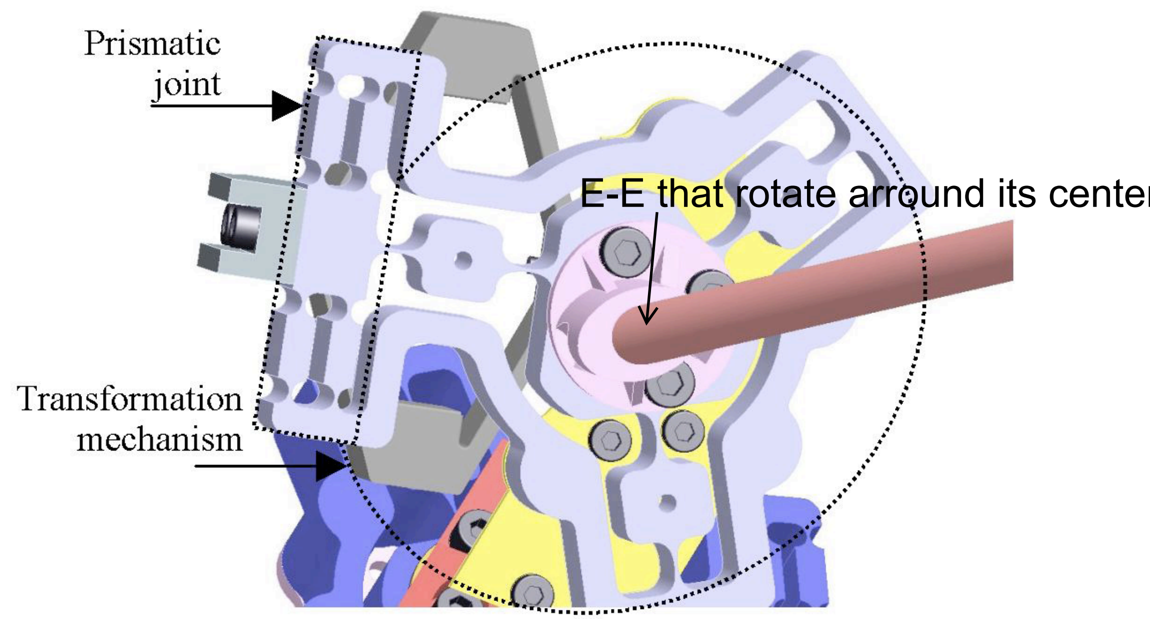
theta dot depends on epsilon, the smaller is epsilon, the bigger is the amplification gain.



example 1: design of an active heart stabilizer

- the parallel structure is equivalent to an actuated revolute joint
- the ratio between the velocity $\dot{q}_2$ and $\dot{\theta}$ can be easily tuned by changing the parameter ϵ to obtain a high rotation/translation ratio
- the structure has interesting stiffness properties when forces in the plane of the mechanism are considered
- out-of-plane stiffness is controlled by the width of the mechanism





ardiolock2: a serial spherical architecture, each actuated revolute joint being obtained by eans of a planar parallel structure in a configuration close to parallel singularity

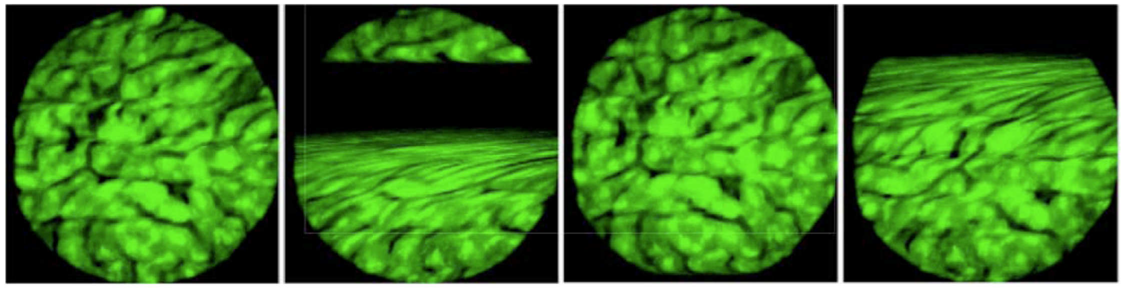
- the parallel structures are controlled with piezo actuators and designed as compliant mechanisms
- the Pseudo Rigid Body Model (PRBM) approach allows to use the previous kinematic analysis

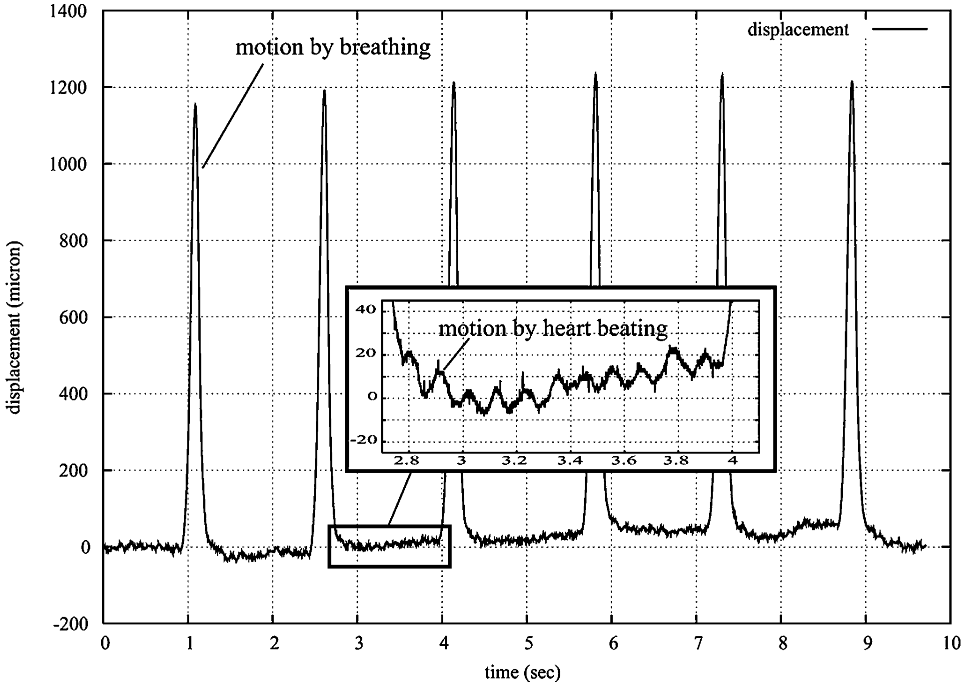
example 2: image stabilization for *in vivo* microscopy

- molecular imaging is a novel technology that visualizes the functions of biological process at the cellular and molecular level within living organism

- confocal microscopy, which is categorized into optical molecular imaging, could have a substantial impact on molecular imaging in that it can provide very high spatial resolution to submicrometers

- small in vivo motion due to heartbeat and breathing makes microscopic observation difficult by blurring the microscope image or impossible by sending a region of interest out of view



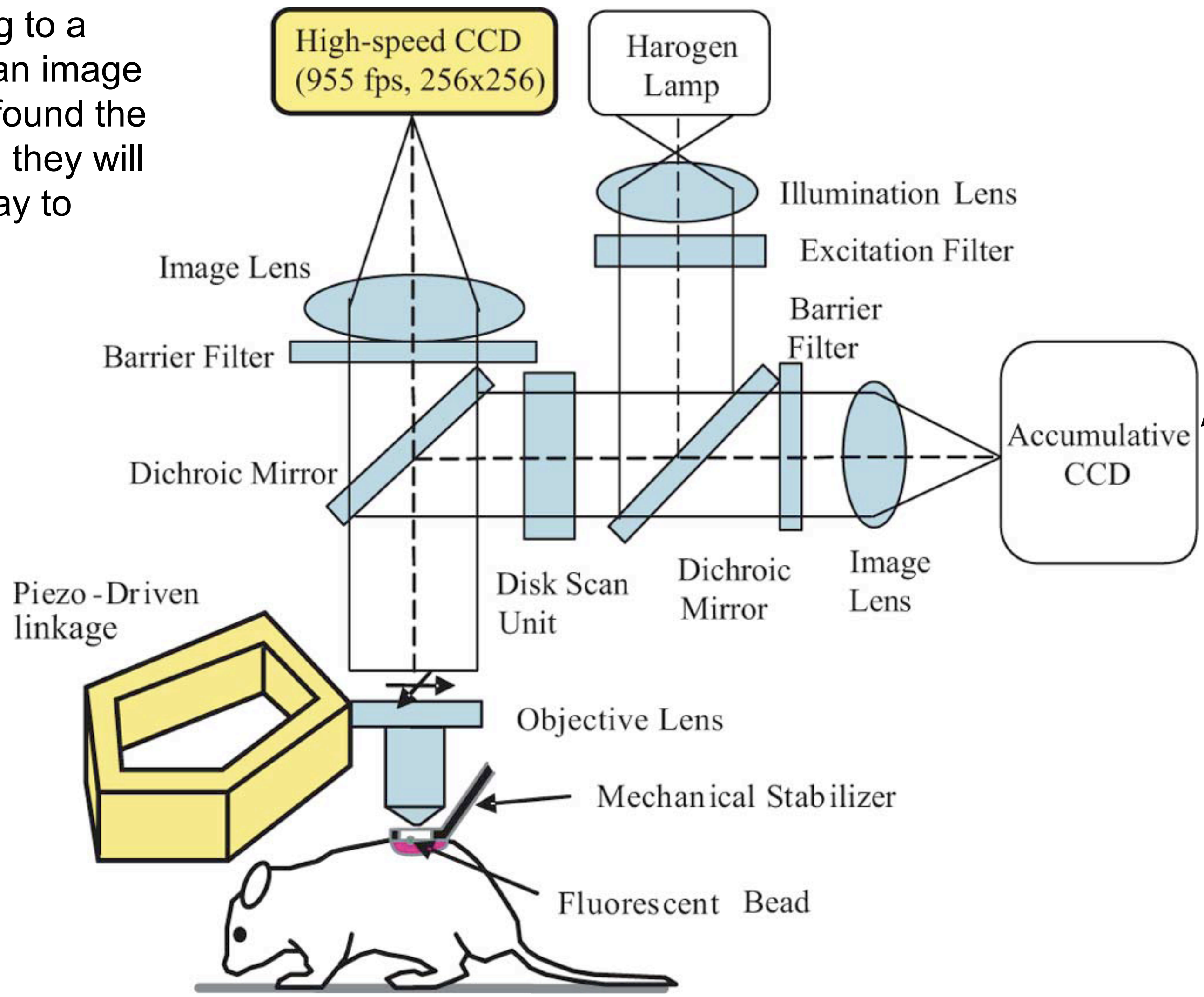


example 2: image stabilization for *in vivo* microscopy

stabilization technology virtually removing the disturbing motion during observation

The idea is to move the lens according to a visual servoing paradigm (if we have an image that is a set of points, once you have found the point of interest-features in the image, they will move accordingly to the camera, in way to keep always the center of the image).

We study how to move the objective lens to keep always the features in camera focus



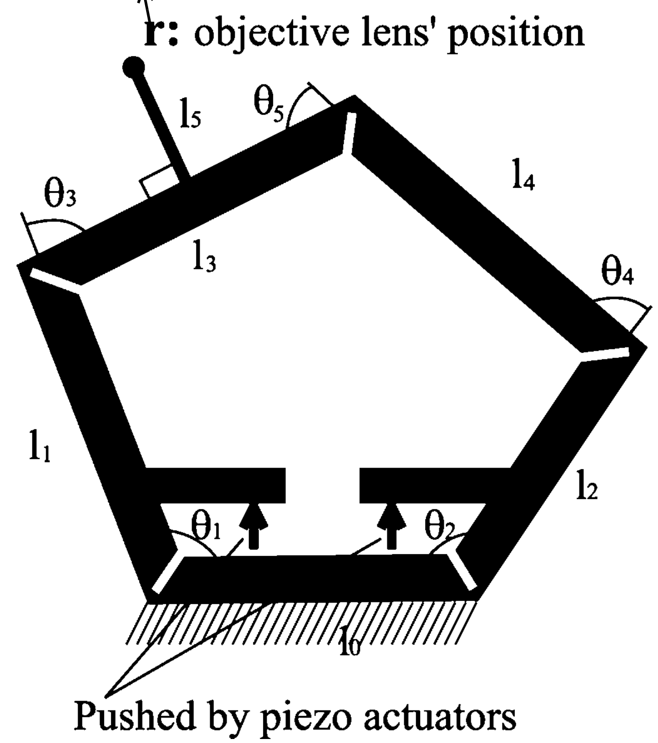
camera that works on a small rate

example 2: image stabilization for *in vivo* microscopy

2 dofs Pentagon   2 joints theta1 and theta2

this point should be moved with small movement

the control is to move r, with a joint velocity that realizes the trajectory that the point does(inverse kinematics)



we have the necessity to transform the linear motion in rotational, because we need to move the rotational joint 2

- a piezoactuator-driven mechanical device   this is analogous to the previous ex
- transfers the movement of actuators to the movement of the objective lens and amplifies the insufficient strokes of the actuators
- two piezoactuators push linkages l_1 and l_2
- the mechanism should have: 1) sufficient enlargement ratio; 2) more isotropic enlargement
- these two properties can be obtained through the jacobian matrix $\mathbf{J}_{\text{rob}}$ relating the e.e. velocity to actuated joints velocities

because they are those to control

$$\dot{\mathbf{r}} = \mathbf{J}_{\text{rob}}\dot{\theta}_G$$

example 2: image stabilization for *in vivo* microscopy

in order to find which is the relationship between the actuated joint velocity and E-E velocity we open the closed kinematic chain in such a way to obtain 2 independent chains (at the point in which there is the E-E)

- enlargement ration is obtained through the eigenvalues of $\mathbf{J}_{\text{rob}}$
- more isotropic enlargement is obtained by maximizing the min singular value of $\mathbf{J}_{\text{rob}}$
- to determine $\mathbf{J}_{\text{rob}}$ the closed chain is transformed into an equivalent tree structure by virtually cutting some joints in closed loops
- the closed loop imposes the constraint that the velocity of the left link computed from θ_1 and θ_3 should be equal to that of the right link from θ_2, θ_4 and θ_5

$$\dot{\mathbf{r}} = \begin{pmatrix} J_1 & J_3 \end{pmatrix} \begin{pmatrix} \dot{\theta}_1 \\ \dot{\theta}_3 \end{pmatrix} = \begin{pmatrix} J_2 & J_4 & J_5 \end{pmatrix} \begin{pmatrix} \dot{\theta}_2 \\ \dot{\theta}_4 \\ \dot{\theta}_5 \end{pmatrix}$$

where $J_i = \frac{\partial \mathbf{r}}{\partial \theta_i}$

- dividing this equation into actuated and unactuated joints

$$\underline{J_S \dot{\theta}_s = -J_G \dot{\theta}_G}$$

with $\theta_s = (\theta_3 \ \theta_4 \ \theta_5)^T$, $\underline{J_S = (J_3 \ \ -J_4 \ \ -J_5),\ J_G = (J_1 \ \ -J_2)}$

- the unactuated joints can be obtained as

from this it's possible to compute the passive joint velocity

$$\dot{\theta}_S = -J_S^{\#} J_G \dot{\theta}_G$$

example 2: image stabilization for *in vivo* microscopy

- providing

$$\dot{\mathbf{r}} = \begin{pmatrix} J_1 & J_3 \end{pmatrix} \begin{pmatrix} \dot{\theta}_1 \\ \dot{\theta}_3 \end{pmatrix} = \begin{pmatrix} J_1 & J_3 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ \multicolumn{2}{c}{J_A} \end{pmatrix} \begin{pmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \end{pmatrix}$$

where J_A is the first row of $-J_S^{\#} J_G$

- thus

$$\mathbf{J}_{\text{rob}} = \begin{pmatrix} J_1 & J_3 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ \multicolumn{2}{c}{J_A} \end{pmatrix}$$

- $\mathbf{J}_{\text{rob}}$ is a function of the link lengths and the joint angles; roughly as the total length of linkages increases, the enlargement ratio increases, but the resonant frequency, which determines the mechanical response, decreases
- a tradeoff has been found through an optimization procedure
- Pentagon amplifies the strokes of two actuators, 180 μm (Physik Instrumente: P-239.90, stroke 180 μm) to 563 μm and 464 μm, respectively

concluding remarks on methodology

- no established methodology, prototipes often result from ad-hoc and/or empirical choices
- some more methodological approaches from the literature
  - robot concept (topological synthesis)
    - objective tree method (5)
    - mimetic approach (6)
  - parameter optimization of a previously defined concept (dimensional synthesis)
    - single objective sinthesis (7)
    - multi-objective synthesis (8)

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