Robotic manipulators in interventional medicine and surgery

Loris Fichera
Cognitive Medical Technology Lab
Robotics Engineering Program
Department of Computer Science
Worcester Polytechnic Institute

Loris Fichera, Ph.D.

Assistant Professor
in Computer Science, Robotics Engineering

Academic Background:
Postdoc in Mechanical Engineering, Vanderbilt University - 2017
PhD in Robotics, Cognition and Interaction Technologies, IIT - 2015
BS/MS in Computer Engineering, University of Catania – 2011

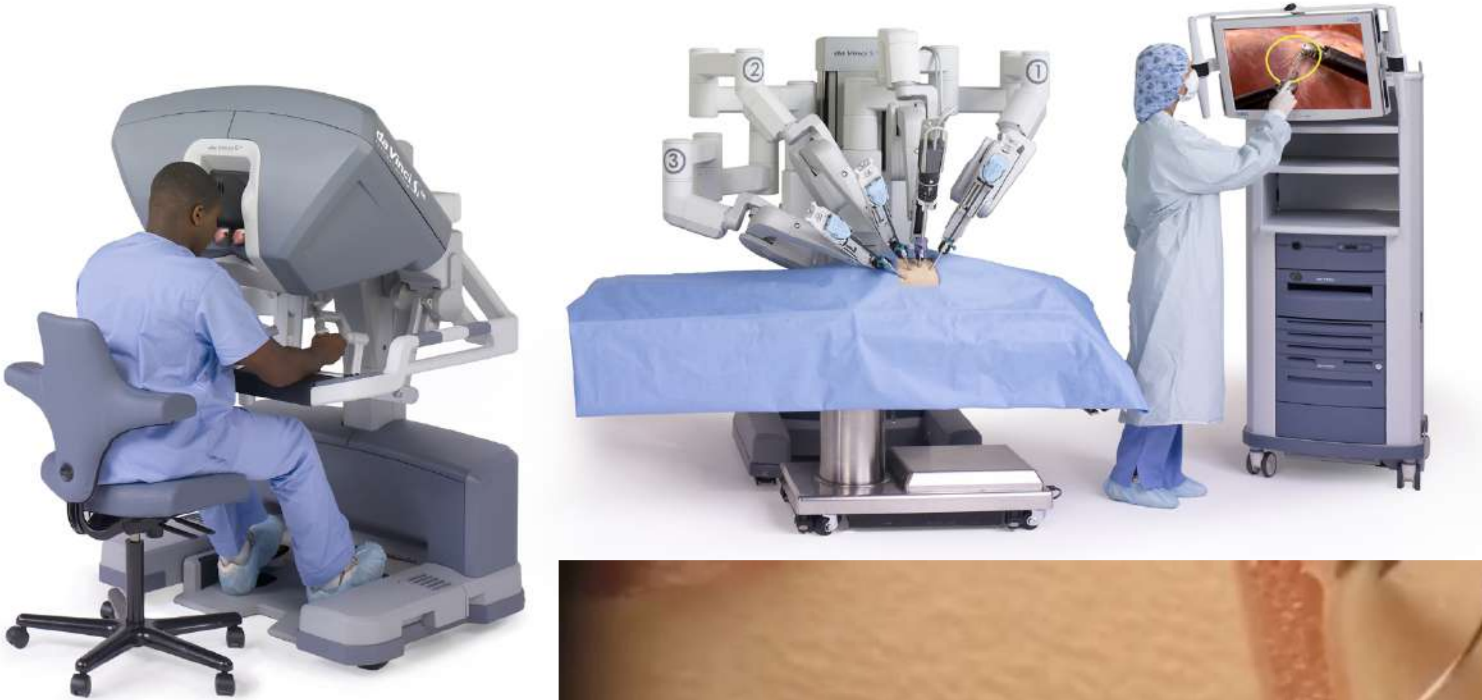

ALLARME INCENDIO
My high school math teacher
Liceo Scientifico Stanislao
Cannizzaro, Vittoria RG
Class of 2005

https://www.youtube.com/watch?v=sRrnW8uga4k

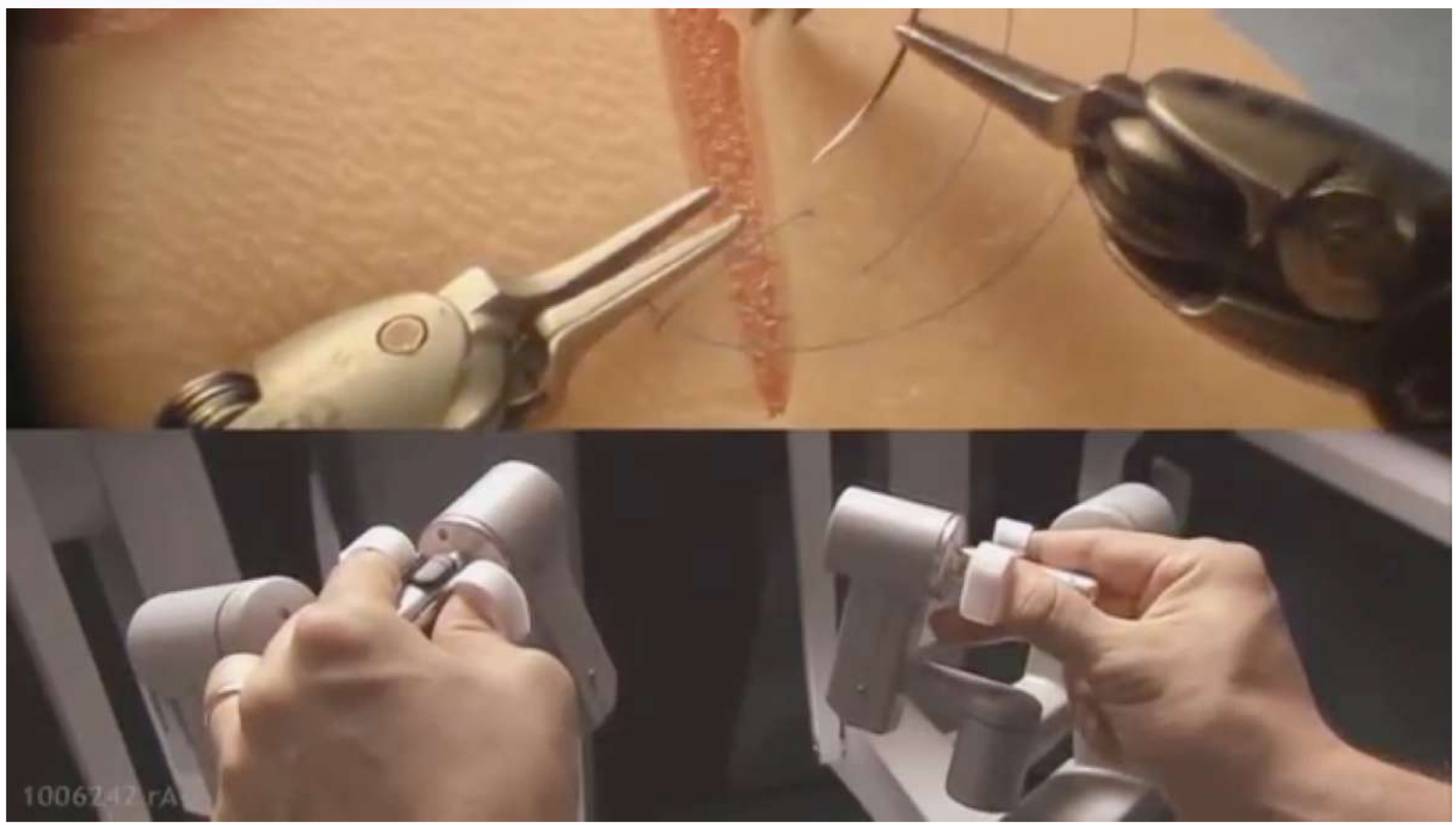
1011948 rA

https://www.youtube.com/watch?v=0XdC1HUp-rU

Robotic technology today



da Vinci surgical System
(© Intuitive Surgical, Inc.)

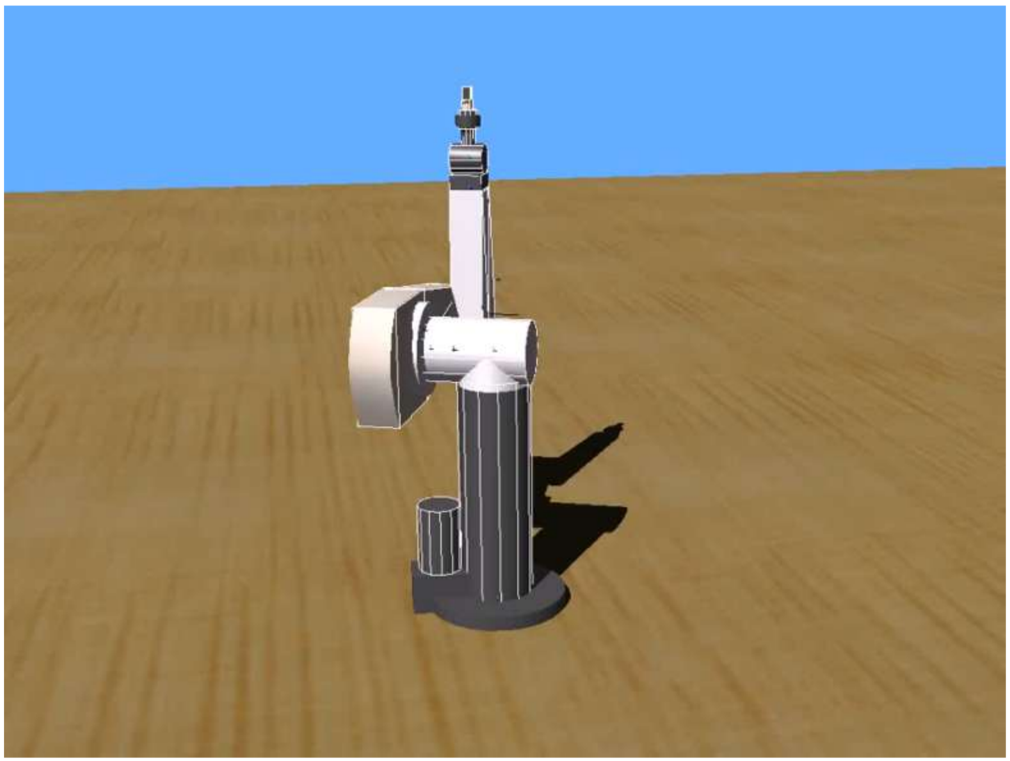


The first surgical robot

Credit: Roger Ressmeyer/CORBIS

Robot kinematics

Goal: describe the *pose* of the robot (position and orientation)



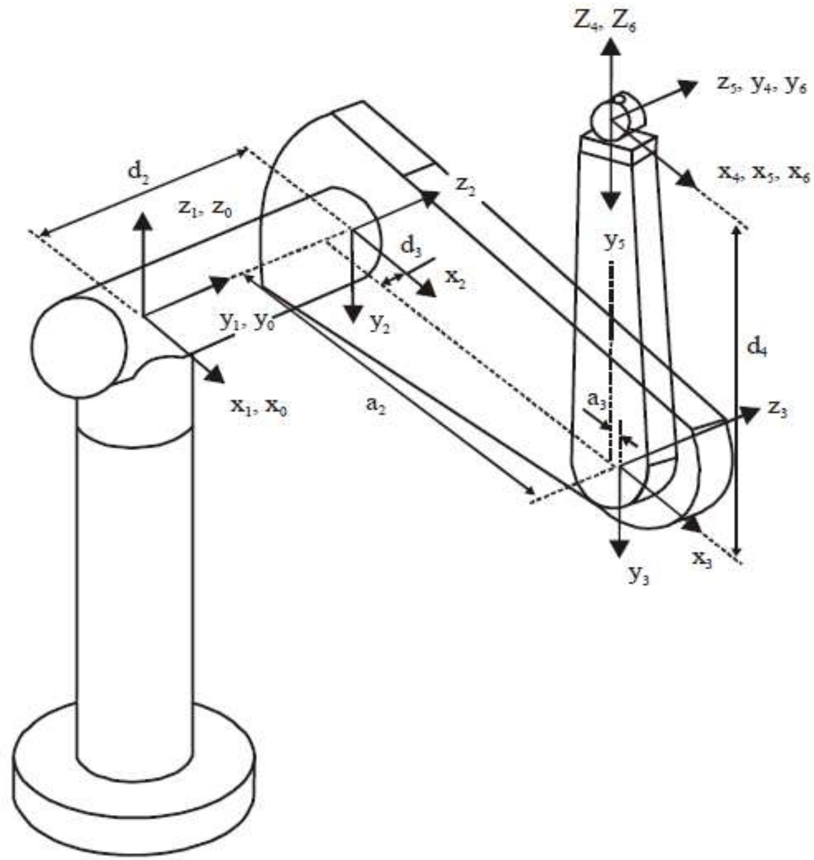


Fig. 1: PUMA 560 in the zero position with attached coordinates frames shown[17]

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

Robot kinematics

Goal: describe the *pose* of the robot (position and orientation)

Transformation matrix between two consecutive joints:

$$T_i^{i+1} = \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Transformation between robot base and end effector:

$$T_0^6 = T_0^1 T_1^2\ T_2^3\ T_3^4\ T_4^5\ T_5^6$$

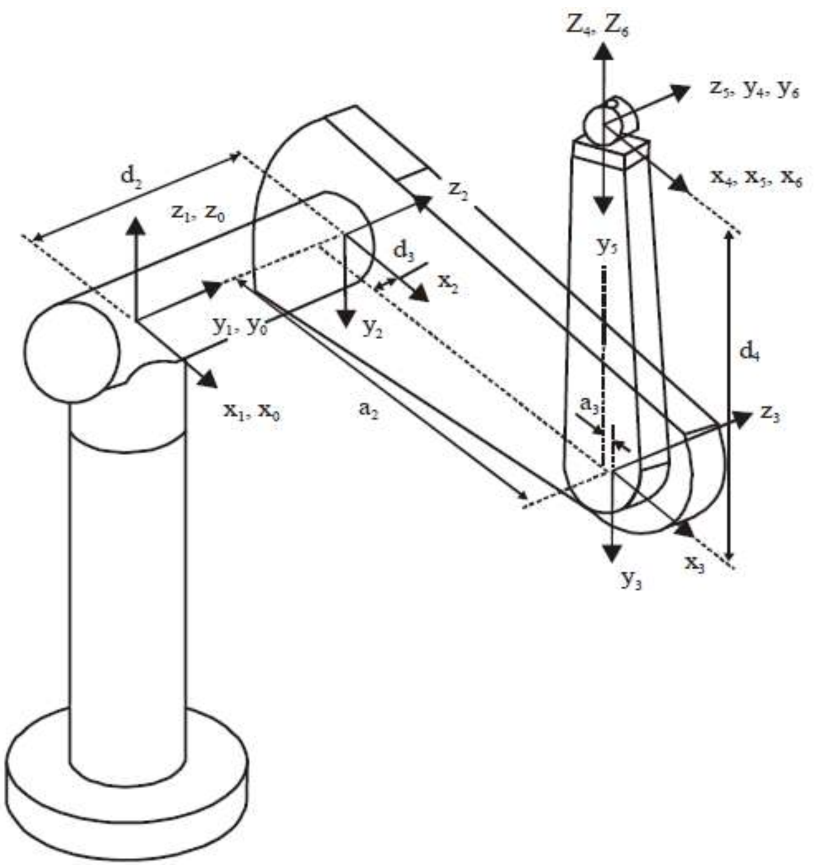


Fig. 1: PUMA 560 in the zero position with attached coordinates frames shown[17]

It may get complex very quickly…

$$ {}^0_6T = {}^0_1T\, {}^1_6T = \begin{bmatrix} r_{11} & r_{12} & r_{13} & p_x \\ r_{21} & r_{22} & r_{23} & p_y \\ r_{31} & r_{32} & r_{33} & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix}. $$

$$ r_{11} = c_1[c_{23}(c_4c_5c_6 - s_4s_5) - s_{23}s_5c_5] + s_1(s_4c_5c_6 + c_4s_6), $$
$$ r_{21} = s_1[c_{23}(c_4c_5c_6 - s_4s_6) - s_{23}s_5c_6 - c_1(s_4c_5c_6 + c_4s_6), $$
$$ r_{31} = -s_{23}(c_4c_5c_6 - s_4s_6) - c_{23}s_5c_6, $$

$$ r_{12} = c_1[c_{23}(-c_4c_5s_6 - s_4c_6) + s_{23}s_5s_6] + s_1(c_4c_6 - s_4c_5s_6), $$
$$ r_{22} = s_1[c_{23}(-c_4c_5s_6 - s_4c_6) + s_{23}s_5s_6] - c_1(c_4c_6 - s_4c_5s_6), $$
$$ r_{32} = -s_{23}(-c_4c_5s_6 - s_4c_6) + c_{23}s_5s_6, $$

$$ r_{13} = -c_1(c_{23}c_4s_5 + s_{23}c_5) - s_1s_4s_5, $$
$$ r_{23} = -s_1(c_{23}c_4s_5 + s_{23}c_5) + c_1s_4s_5, $$
$$ r_{33} = s_{23}c_4s_5 - c_{23}c_5, $$

$$ p_x = c_1[a_2c_2 + a_3c_{23} - d_4s_{23}] - d_3s_1, $$
$$ p_y = s_1[a_2c_2 + a_3c_{23} - d_4s_{23}] + d_3c_1, $$
$$ p_z = -a_3s_{23} - a_2s_2 - d_4c_{23}. $$

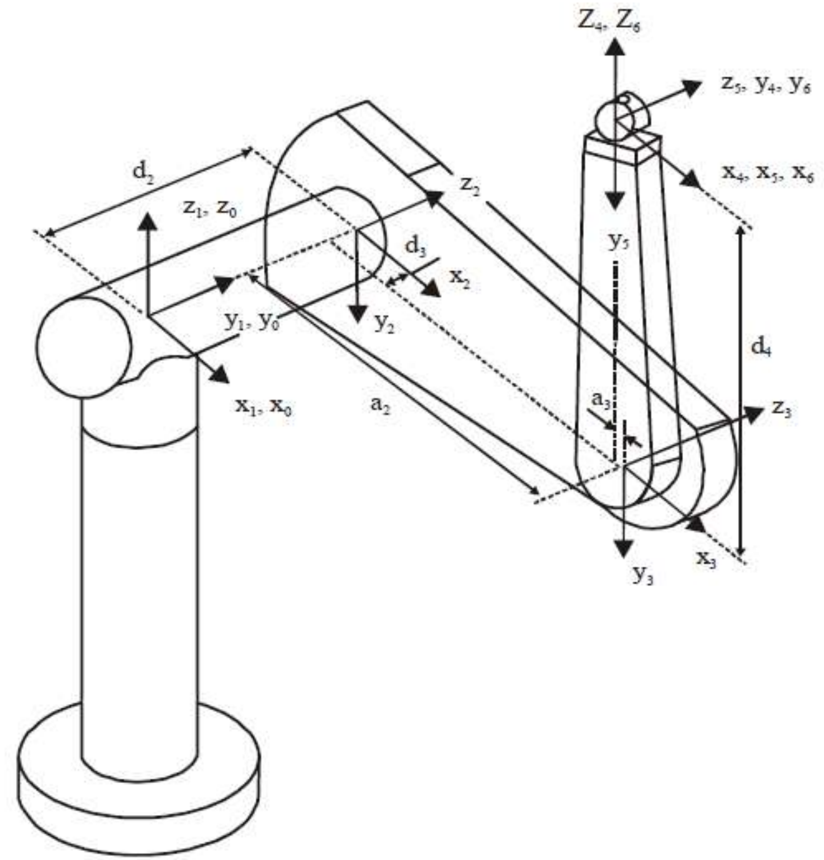


Fig. 1: PUMA 560 in the zero position with attached coordinates frames shown[17]

Inverse Kinematics

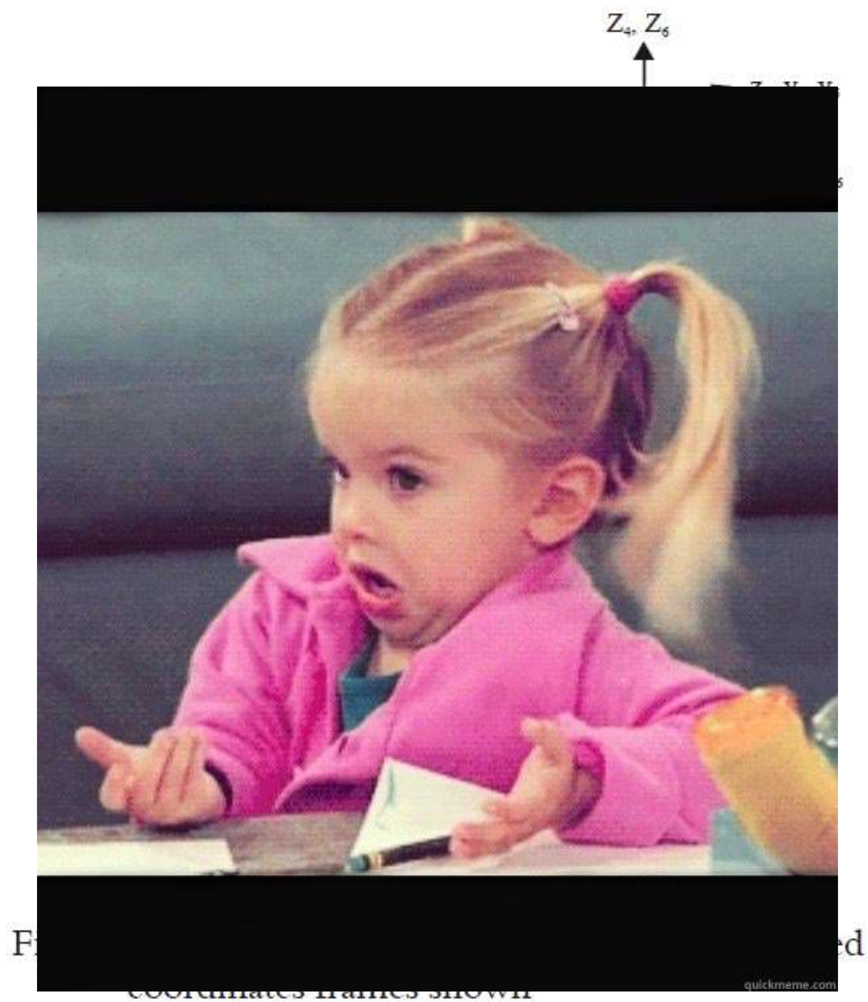
Goal: calculate the joint angles for a desired pose

$$r_{11} = c_1[c_{23}(c_4c_5c_6 - s_4s_5) - s_{23}s_5c_5] + s_1(s_4c_5c_6 + c_4s_6),$$
$$r_{21} = s_1[c_{23}(c_4c_5c_6 - s_4s_6) - s_{23}s_5c_6 - c_1(s_4c_5c_6 + c_4s_6),$$
$$r_{31} = -s_{23}(c_4c_5c_6 - s_4s_6) - c_{23}s_5c_6,$$

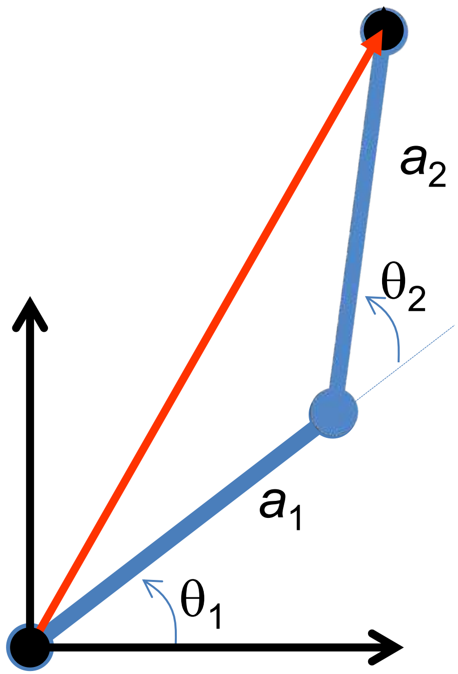
$$r_{12} = c_1[c_{23}(-c_4c_5s_6 - s_4c_6) + s_{23}s_5s_6] + s_1(c_4c_6 - s_4c_5s_6),$$
$$r_{22} = s_1[c_{23}(-c_4c_5s_6 - s_4c_6) + s_{23}s_5s_6] - c_1(c_4c_6 - s_4c_5s_6),$$
$$r_{32} = -s_{23}(-c_4c_5s_6 - s_4c_6) + c_{23}s_5s_6,$$

$$r_{13} = -c_1(c_{23}c_4s_5 + s_{23}c_5) - s_1s_4s_5,$$
$$r_{23} = -s_1(c_{23}c_4s_5 + s_{23}c_5) + c_1s_4s_5,$$
$$r_{33} = s_{23}c_4s_5 - c_{23}c_5,$$

$$p_x = c_1[a_2c_2 + a_3c_{23} - d_4s_{23}] - d_3s_1,$$
$$p_y = s_1[a_2c_2 + a_3c_{23} - d_4s_{23}] + d_3c_1,$$
$$p_z = -a_3s_{23} - a_2s_2 - d_4c_{23}.$$



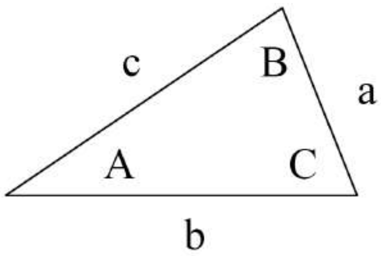
A geometric example



$\vec{W} = (p_{Wx}, p_{Wy})$

$\theta_1 = ?$ $\quad \theta_2 = ?$

Law of Cosines



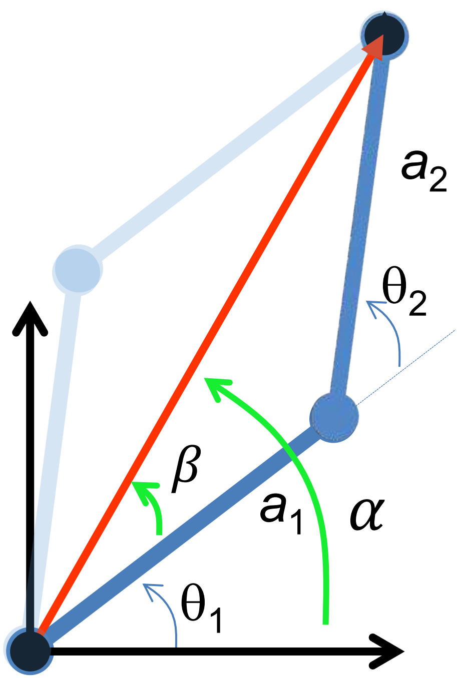
$$a^2 = b^2 + c^2 - 2bc \cos A$$

$$\cos A = \frac{b^2 + c^2 - a^2}{2bc}$$

$$\cos(\pi - \theta_2) = \frac{a_1^2 + a_2^2 - (p_{Wx}^2 + p_{Wy}^2)}{2a_1 a_2}$$

$$\cos(\theta_2) = -\frac{a_1^2 + a_2^2 - (p_{Wx}^2 + p_{Wy}^2)}{2a_1 a_2}$$

A geometric example



$$\vec{W} = (p_{Wx}, p_{Wy})$$

$\theta_1 = ?$ $\theta_2 = ?$

$$\theta_1 = \alpha \pm \beta$$

$$\alpha = \tan^{-1}\left(\frac{p_{Wy}}{p_{Wx}}\right)$$

$$\beta = \cos^{-1}\left(\frac{a_1^2 + p_x^2 + p_y^2 - a_2^2}{2a_1\sqrt{p_{Wx}^2 + p_{Wy}^2}}\right)$$

$$\cos(\theta_2) = -\frac{a_1^2 + a_2^2 - (p_{Wx}^2 + p_{Wy}^2)}{2a_1 a_2}$$

Inverse Kinematics

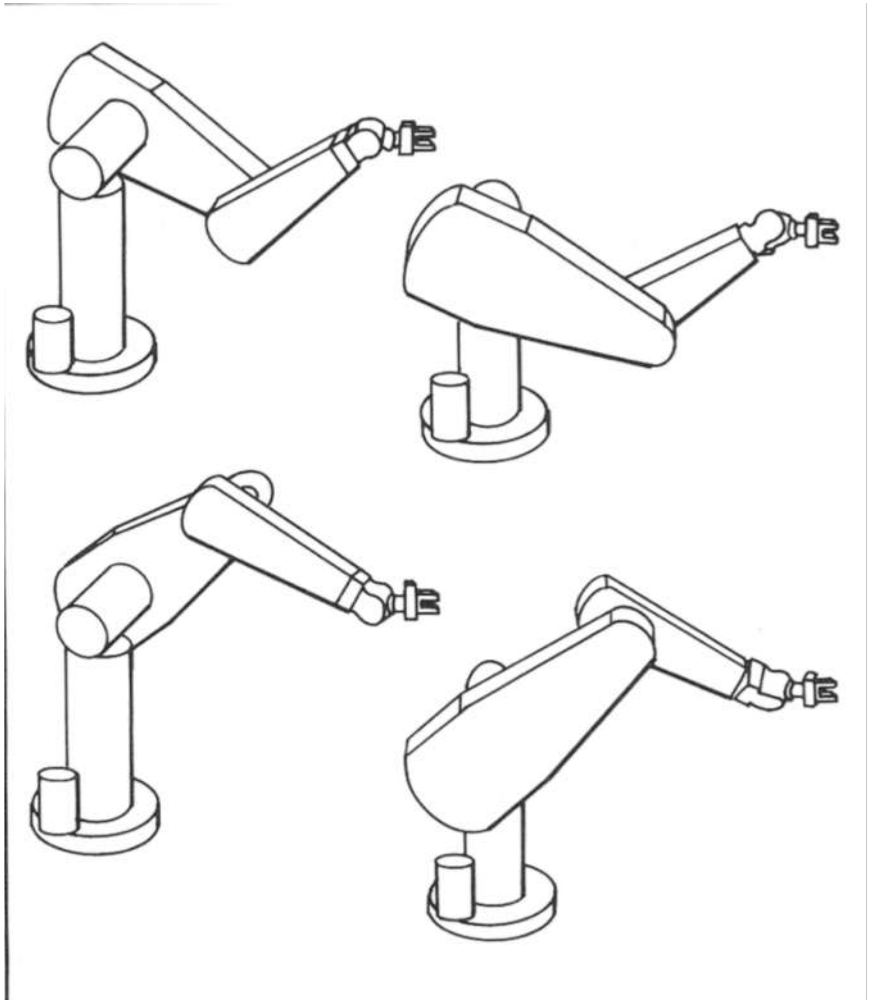
Even if we find an analytic inverse, the problem may still have zero/multiple/infinite solutions!

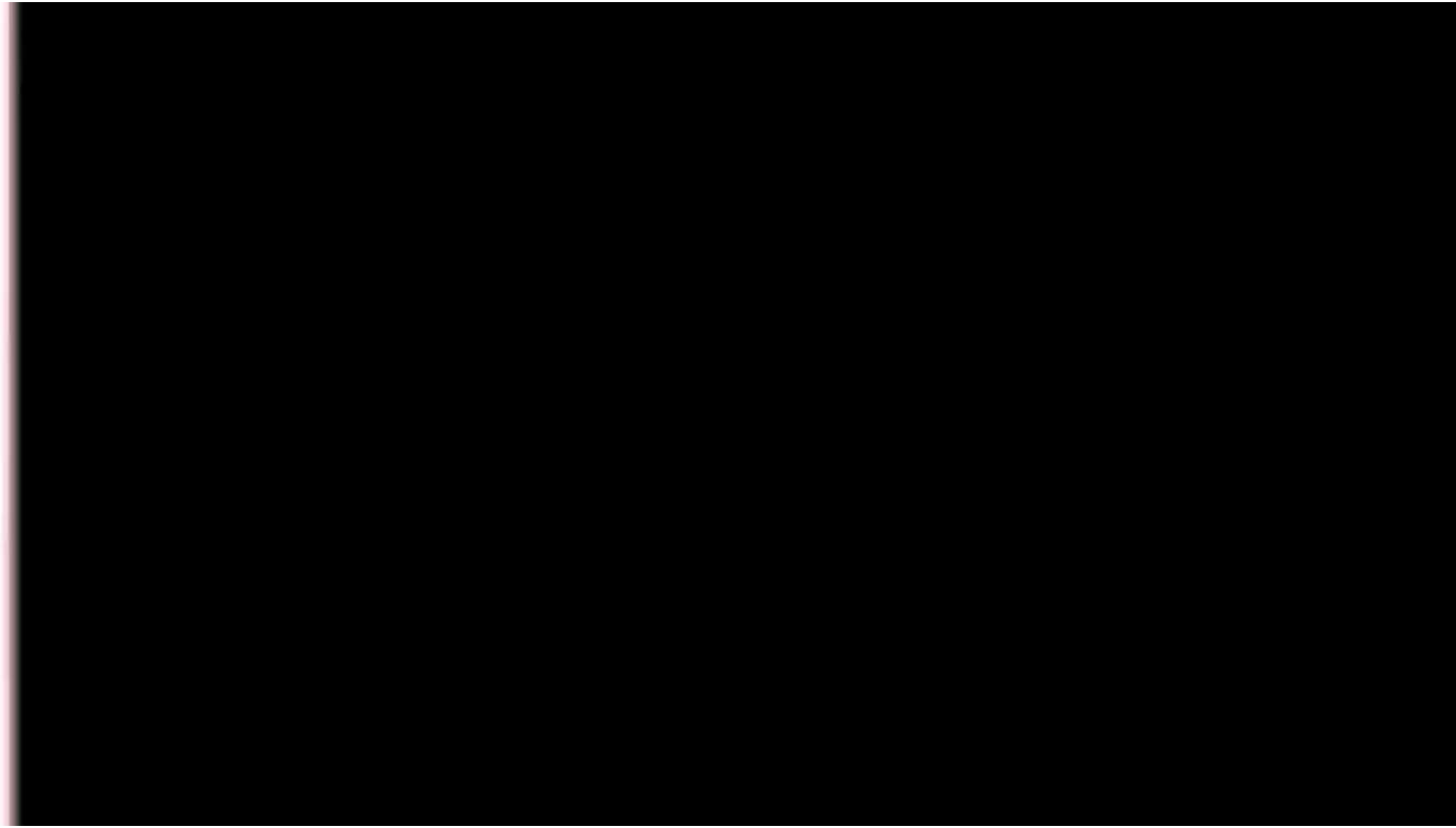
$$r_{11} = c_1[c_{23}(c_4c_5c_6 - s_4s_5) - s_{23}s_5c_5] + s_1(s_4c_5c_6 + c_4s_6),$$
$$r_{21} = s_1[c_{23}(c_4c_5c_6 - s_4s_6) - s_{23}s_5c_6 - c_1(s_4c_5c_6 + c_4s_6),$$
$$r_{31} = -s_{23}(c_4c_5c_6 - s_4s_6) - c_{23}s_5c_6,$$

$$r_{12} = c_1[c_{23}(-c_4c_5s_6 - s_4c_6) + s_{23}s_5s_6] + s_1(c_4c_6 - s_4c_5s_6),$$
$$r_{22} = s_1[c_{23}(-c_4c_5s_6 - s_4c_6) + s_{23}s_5s_6] - c_1(c_4c_6 - s_4c_5s_6),$$
$$r_{32} = -s_{23}(-c_4c_5s_6 - s_4c_6) + c_{23}s_5s_6,$$

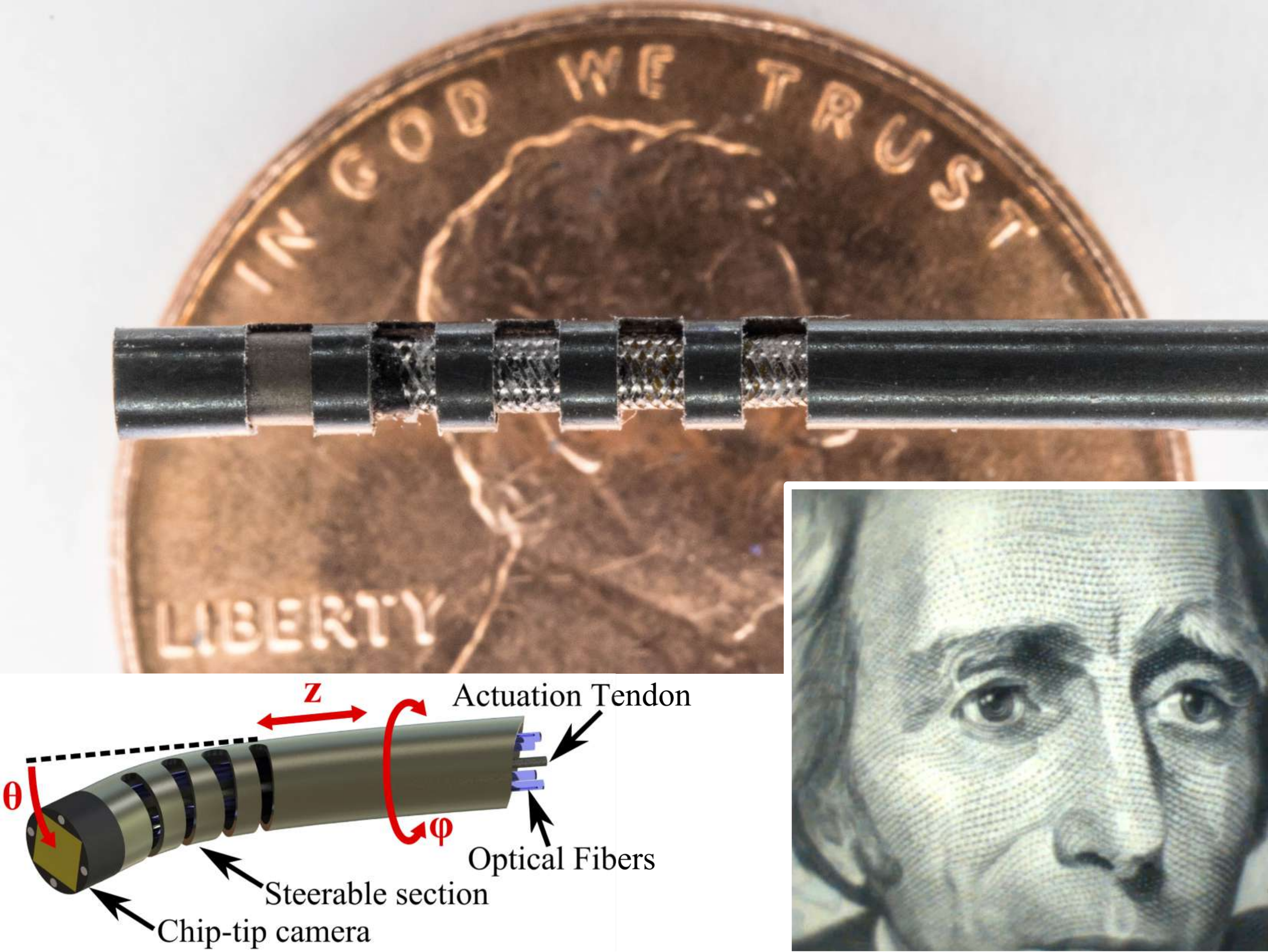
$$r_{13} = -c_1(c_{23}c_4s_5 + s_{23}c_5) - s_1s_4s_5,$$
$$r_{23} = -s_1(c_{23}c_4s_5 + s_{23}c_5) + c_1s_4s_5,$$
$$r_{33} = s_{23}c_4s_5 - c_{23}c_5,$$

$$p_x = c_1[a_2c_2 + a_3c_{23} - d_4s_{23}] - d_3s_1,$$
$$p_y = s_1[a_2c_2 + a_3c_{23} - d_4s_{23}] + d_3c_1,$$
$$p_z = -a_3s_{23} - a_2s_2 - d_4c_{23}.$$





https://www.youtube.com/watch?v=_c6F7mJpSRI

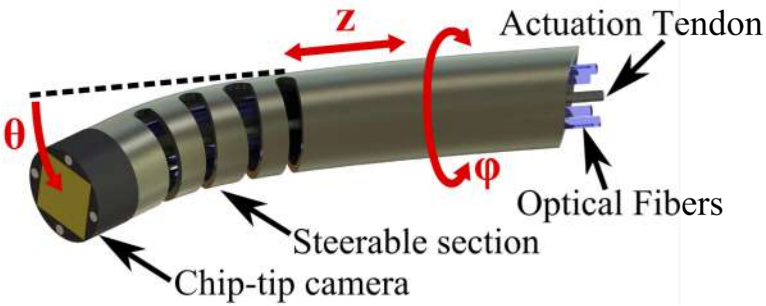


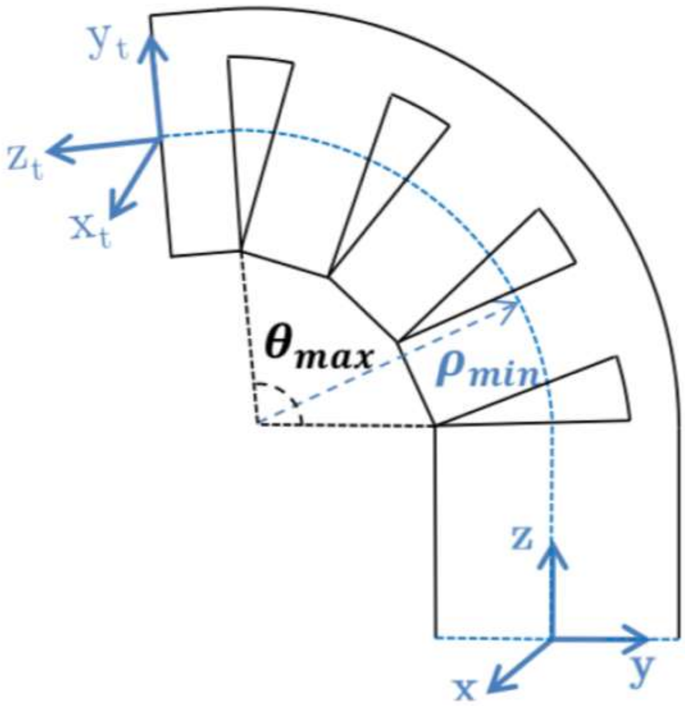
IN GOD WE TRUST
LIBERTY
z
θ
φ
Actuation Tendon
Optical Fibers
Steerable section
Chip-tip camera

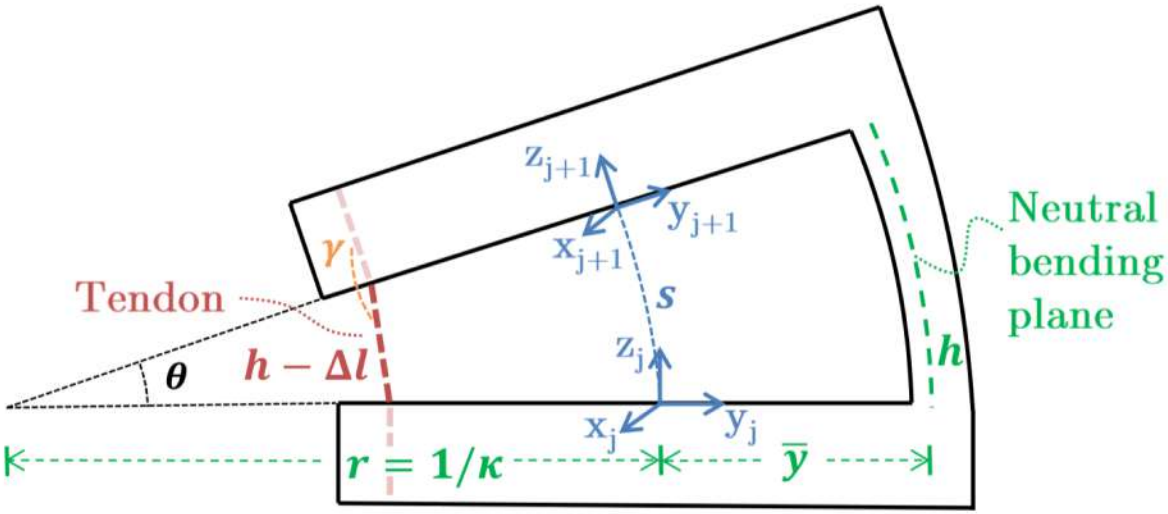
https://www.youtube.com/watch?v=0nZ7vTxpLQU

Fichera L et al, **Through the Eustachian Tube and Beyond: A New Miniature Robotic Endoscope to See Into the Middle Ear**, Robotics and Automation Letters (2017)

Endoscope kinematics



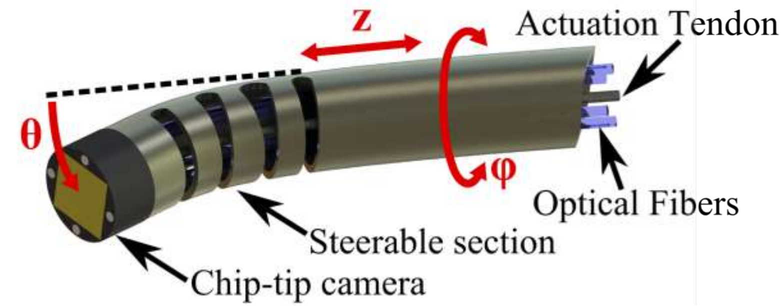


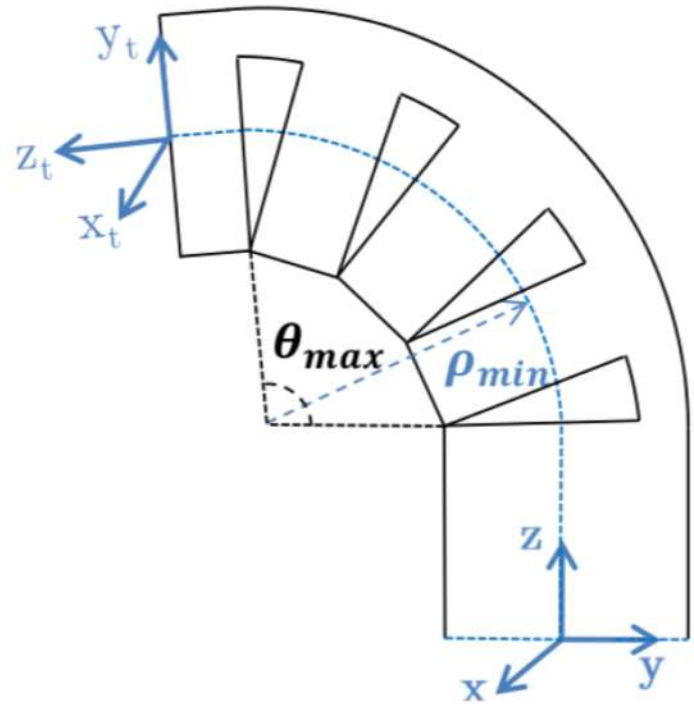


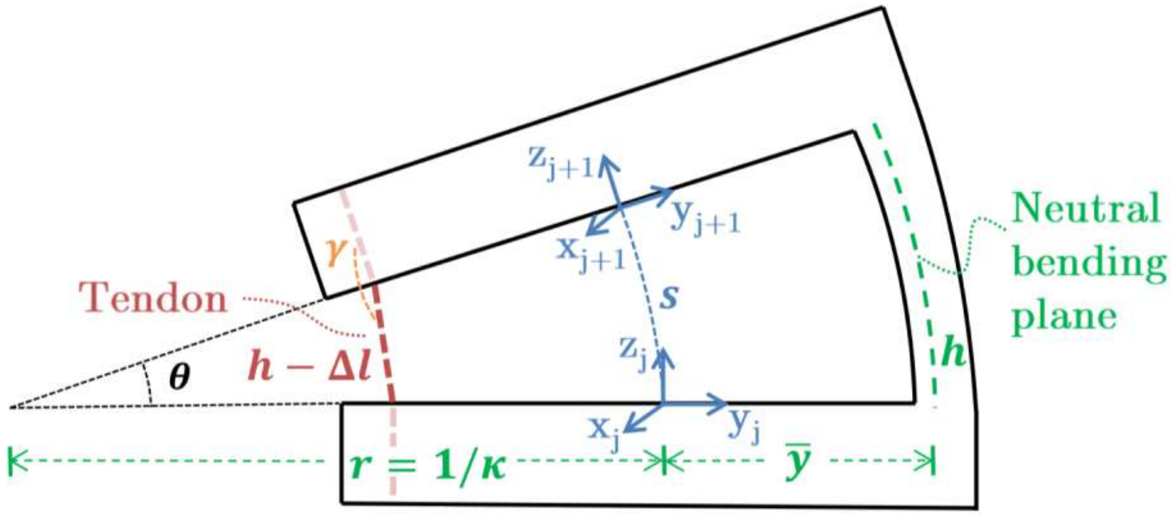
$$\kappa \approx \frac{\Delta l}{h(r_i + \bar{y}) - \Delta l\, \bar{y}} \quad s = \frac{h}{1 + \bar{y}\kappa}$$

York P. et al, **A wrist for needle-sized surgical robots,** ICRA 2015

Endoscope kinematics



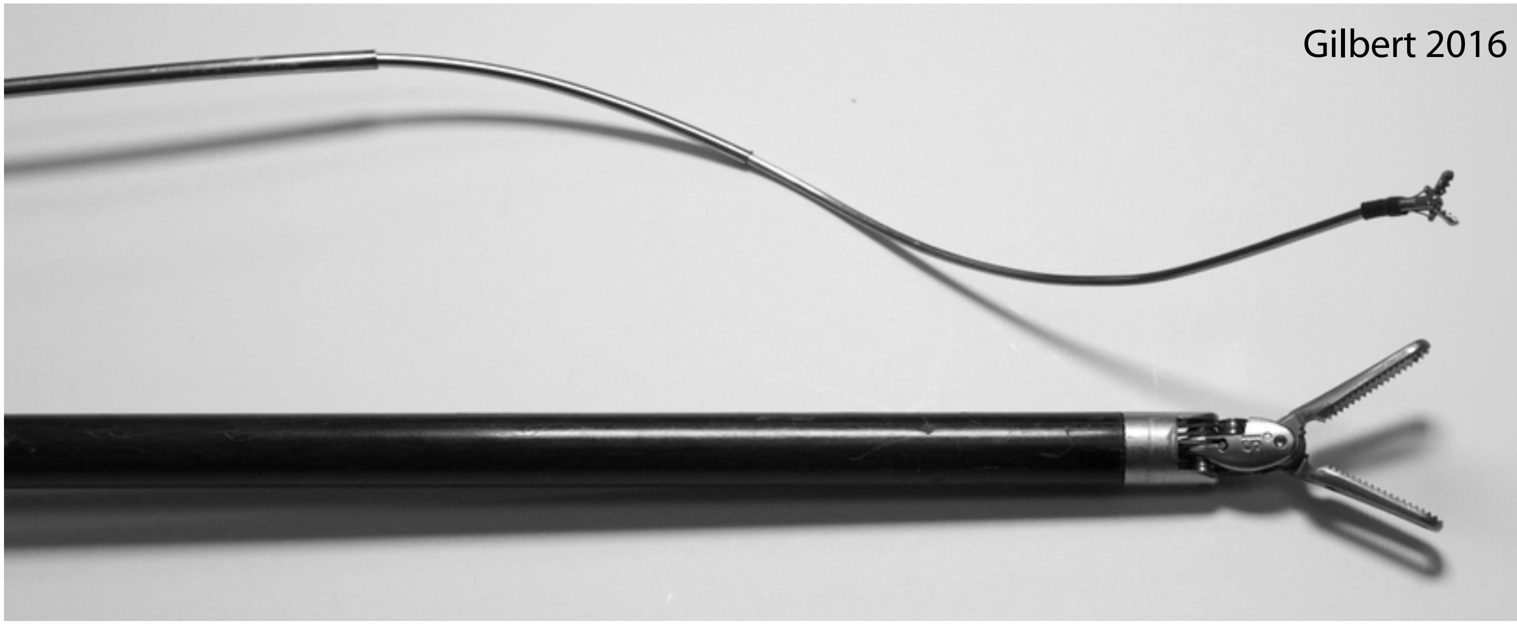


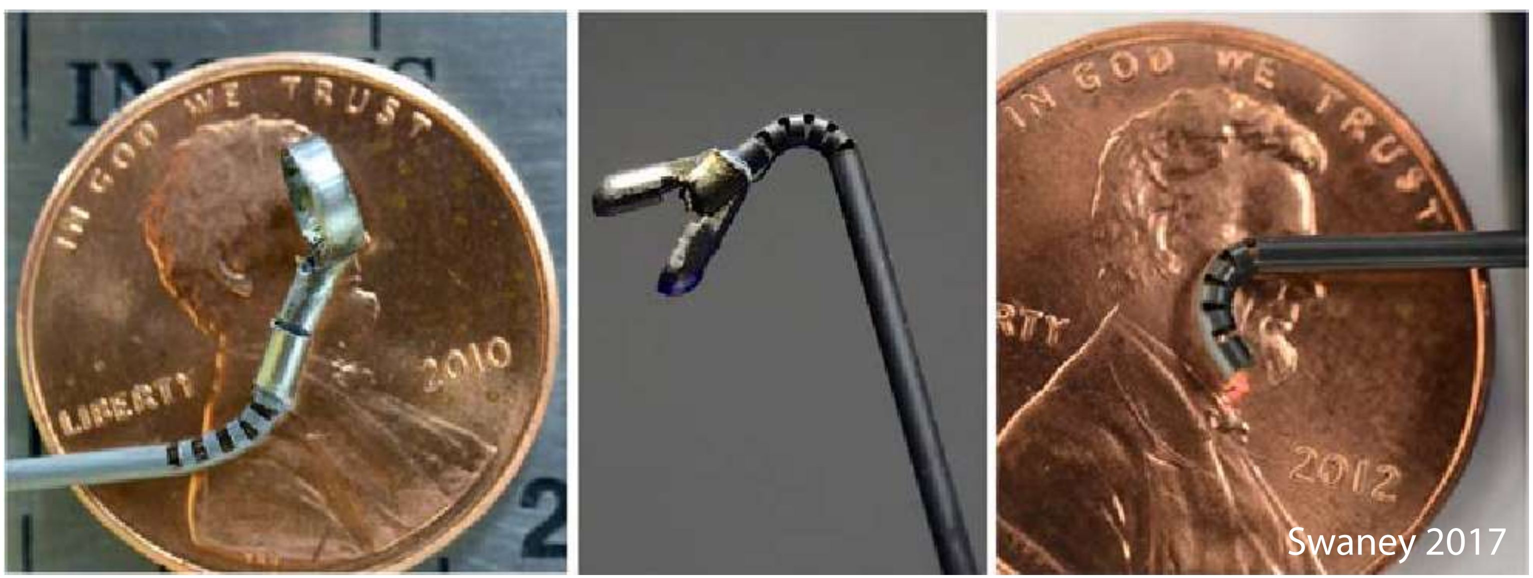


$$T_j^{j+1} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(\kappa s) & -\sin(\kappa s) & (\cos(\kappa s) - 1)/\kappa \\ 0 & \sin(\kappa s) & \cos(\kappa s) & \sin(\kappa s)/\kappa \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

York P. et al, **A wrist for needle-sized surgical robots,** ICRA 2015

Continuum robots in surgery





The Rise of Robots in the Operating Room | Dr. Robert Webster III | TEDxNashvilleSalon

https://www.youtube.com/watch?v=Mr4xEH11N5A

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