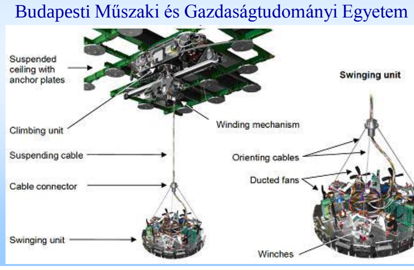
Szabadságfokok, avagy robotok a mennyezeten

Stépán Gábor
Műszaki Mechanikai Tanszék
Budapesti Műszaki és Gazdaságtudományi Egyetem



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Motivation

ACROBOTER

Autonomous Collaborative Robots
to Swing and Work
in Everyday EnviRonment

Sixth Framework Project
Priority 2.6.1. (Advanced Robotics)
Specific Targeted Research Project

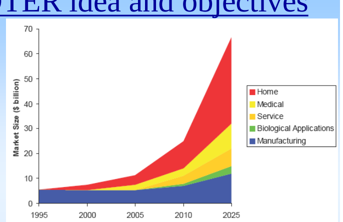
The consortium

1	BME	Budapest University of Technology and Economics (HU)
2	LU	Lund University (S)
3	FIPK	Fraunhofer IPK (D)
4	DUTH	Democritus University of Thrace (EL)
5	ROBO	Robosoft SA (F)
6	UREAD	University of Reading (UK)
7	ROBOTNIK	Robotnik Automation SLL (E)

Academic partners ☐ Industrial partners ☐

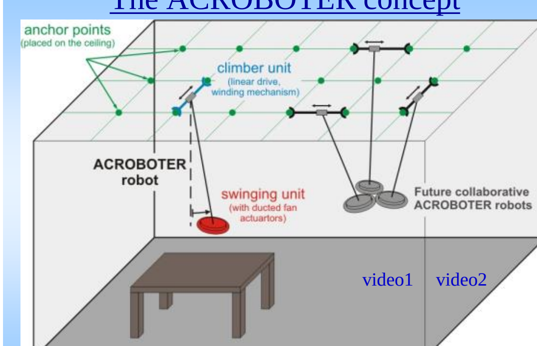
The ACROBOTER idea and objectives

Service robots –
- Ground based
- Wall based
- **Ceiling based**
- Air based



ACROBOTER aims
- to develop radically new robot locomotion
- in **home** and/or in work environments
- to manipulate small objects autonomously or in close cooperation with humans. video1 video2

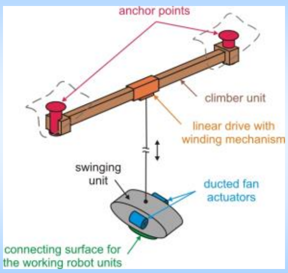
The ACROBOTER concept



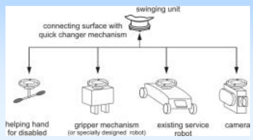
video1 video2

The ACROBOTER subsystems

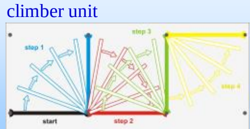
Main components



Examples for connecting tools

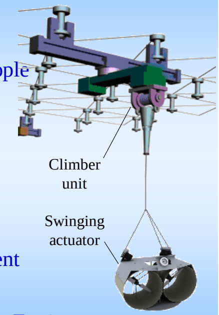


Stroboscopic movement of the climber unit



Application scenarios

- Cleaning
- **Tidying a (seminar) room**
- Assistance to young/elderly people
- Movement rehabilitation
- **Pick and place**
- Haptic interface
- Tourist guide
- Move cameras in auditoriums
- Decoration/lighting/entertainment
- Green house robot
- Robot in Collaborative Working Environments



Motivation

Motivation

ACROBOTER competitors

	Robotic toys	Robotic vacuums	Humanoids	Flexibot	Acroboter
Has real market potential for everyday applications	✓	✓	✕	✓	✓ depends
Special installation is needed	✕	✕	✕	✓	✓ minor
Can entertain people	✓	✕	✓	✕	✓
Can help the disabled		✓	✓	✓	✓
Can co-operate with people			✓	✓	✓
Can exercise patient					✓
Can carry small objects			✓		✓
Has weight/payload ratio near above 1:1					✓ almost
Can reach above 2 metres				✓	✓
Can move in 3D space incl. the whole cubic volume of a room					✓

ACROBOTER Fills the Gap

ACROBOTER competitors (cntn'd)

	Robotic toys	Robotic vacuums	Humanoids	Flexibot	Acroboter
The workspace should not be prepared before operation				✓	✓
Provides an open architecture platform for service robots					✓
Works continuously without battery recharge (no battery)				✓	✓
Can move fast in a room		✓			✓ no
Can avoid any obstacles in a room					✓

ACROBOTER Fills the Gap

Technical data

Description	Goal ('06) ATR('08) FR['10]
Horizontal speed	**5 [m/s] (0.5 - 1.0) [0.5 - 1.0]**
Vertical speed	**10 [m/s] (2 - 4) [2 - 4]**
Horizontal acceleration	**9.81 [m/s^2] (1) [1]**
Vertical acceleration	**9.81 [m/s^2] (9.81) [9]**
Accuracy (position / path)	**± 3 [mm] (10 / 50) [10 / 50]**
Own weight of the CU	**35 [kg] (35) [35]**
Own weight of the SU	**5 [kg] (7) [7.7]**
Load capability	**5 [kg] (5) [5]**
Cost	**15000 EUR + 100 EUR/m2 of the covered area 5 [kg] (-) [reduce after substantial design refinement]**

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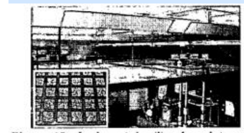
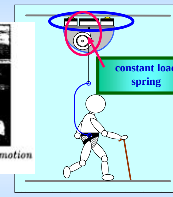
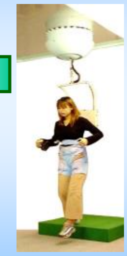
Competitors – FLORA

Cable suspended walking assistant







Permanent magnet based traction (2008)

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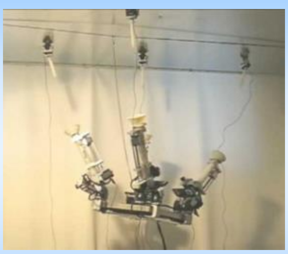
Competitors – SPIDERBOT



It walks on ceiling by shooting retractable suction cups
(Ben Gurion University, 2009)

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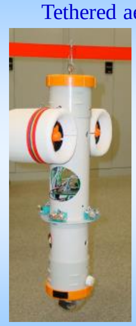
Competitors

Tethered aerial robot for rescue tasks



Philip J. McKerrow, Danny Ratner, The design of a tethered aerial robot, in *Proceedings of the IEEE International Conference on Robotics and Automation*, Roma, Italy, 10-14 April 2007

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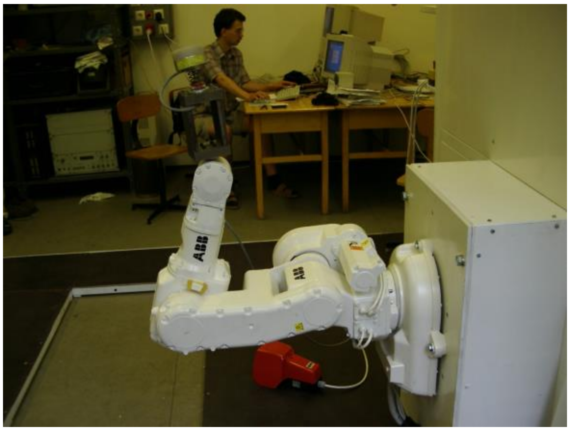
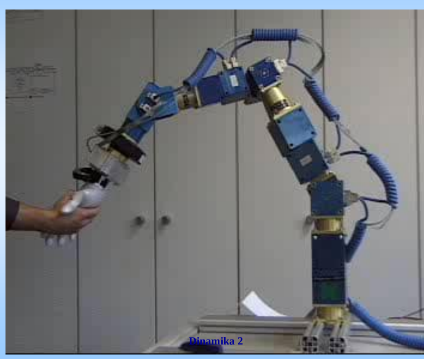


Kézfogás és 7 DoF



Kézfogás és 7 DoF

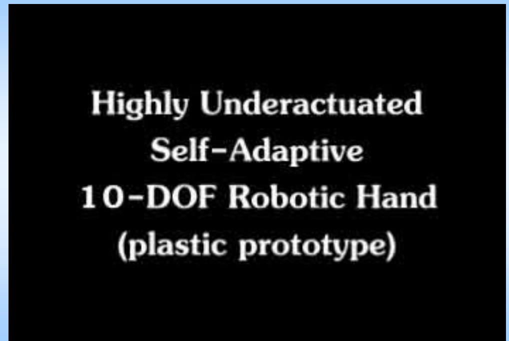
7 DoF az iparban

Kétszer 6DoF az iparban

Dinamika 2

Under-actuated fingers

Under-actuated fingers



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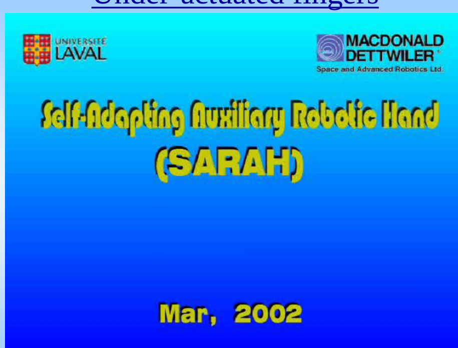
Under-actuated fingers



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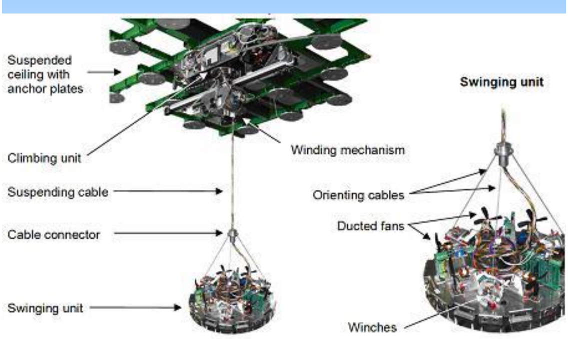

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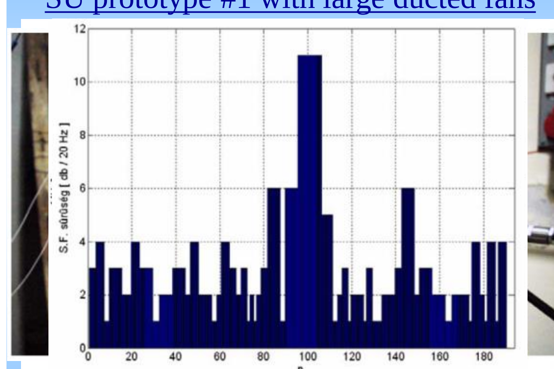
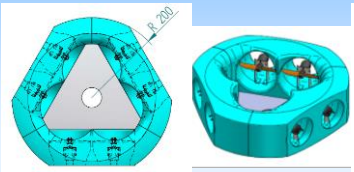
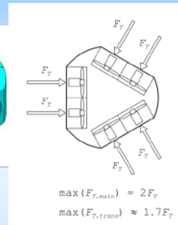
SU prototype #1 with large ducted fans



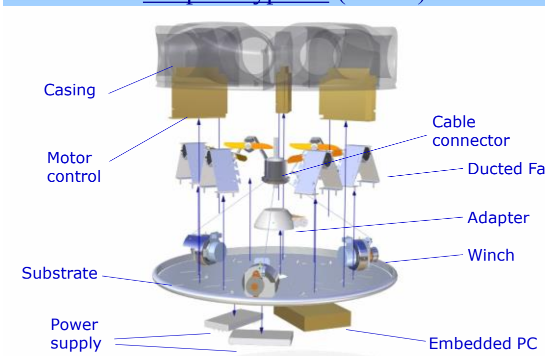
SU prototype #2 with 6 identical ducted fans





- reduced vertical dimension
- increased manoeuvrability
- 3 cable winding motors (not shown in the figure)
- 6 small sized and identical ducted fans (counts 3 actuators)
- blades optimized for thrust and noise

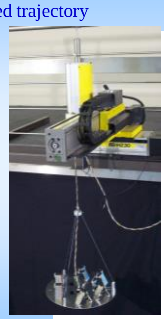
SU prototype #2 (cont'd)

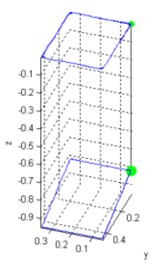


SU #2 integrated with Hirata 3D robot

Stabilization around a desired trajectory

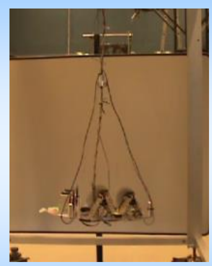
Single pendulum based path planning

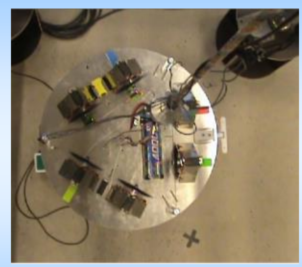




Pendulum test video **Comparison test video**

SU #2 positioning with ducted fans

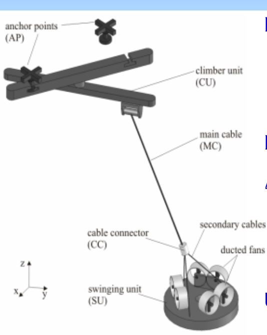




Rectangle (side view) **Rectangle (top view)** **Nutation**

Rectangle (side view)

Prototype #3 – under-actuated & redundant



Degrees of freedom: **12** DoF
- Climber unit (CU) ⇒ 3 DoF
- Cable connector (CC) ⇒ 3 DoF
- Swinging unit (SU) ⇒ 6 DoF

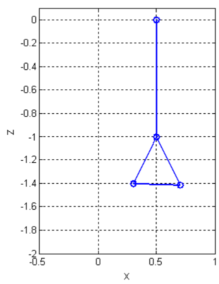
Highly **redundant**: 12 > 6

Actuators:
- RRT climber unit ⇒ 3
- 1 + 3 windable cables ⇒ 4
- 6 Ducted fan actuators ⇒ 3

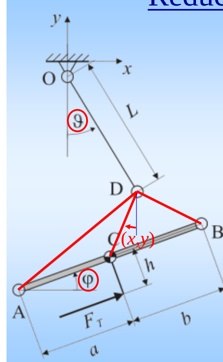
Under-actuated
- 10 Actuators < 12 DoF

Contents

Under-actuated system dynamics



Reduced planar model



System – 4 DoF : $\mathbf{q} = [\, x, y, \varphi, \vartheta \,]^{\mathrm{T}}$

- Bar **AB** models the swinging actuator and the payload together
- Center of gravity (with payload): C (x,y)
- Fixed suspension point only
- The main cable **OD** is constant length L

Actuators – 3 :

- winding units at A and B orientate the load via the lengths of cables **AD** and **BD**
- The (only) single thrust force of the ducted fan is F_T

Task – 3 DoF :

- move C on the desired trajectory x^d, y^d
- keep the desired orientation φ^d

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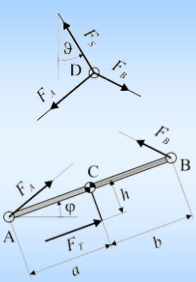
Under-actuated and redundant



Free body diagrams

General coordinates: $\dim_q = 4$

Control inputs:

- Secondary cable forces F_A and F_B,
- Thrust force F_T,
- $\dim_u = 3 < \dim_q \rightarrow$ under-actuated

$$\ddot{\mathbf{q}} = \mathbf{f}(\mathbf{q}, \dot{\mathbf{q}}) + \mathbf{G}(\mathbf{q})\,\mathbf{u}$$

Task:

- the task is described by $\dim_{task}$ number of independent scalar functions: φ^d, x^d, y^d,
- $\dim_{task} = 3 < \dim_q \rightarrow$ kinematically redundant

Still, *unique solution* for **q** and **u**

For the case $\dim_u = \dim_{task}$

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Theoretical solution for the inverse task

$$\ddot{\tilde{\mathbf{q}}} = \mathbf{f}(\tilde{\mathbf{q}}, \dot{\tilde{\mathbf{q}}}) + \mathbf{G}(\tilde{\mathbf{q}})\,\mathbf{u}$$

active and *passive* coordinate separation: $\tilde{\mathbf{q}} \rightarrow \mathbf{q} = \begin{pmatrix} \mathbf{q}_a \\ \mathbf{q}_p \end{pmatrix}$

$$\begin{bmatrix} \ddot{\mathbf{q}}_a \\ \ddot{\mathbf{q}}_p \end{bmatrix} = \begin{bmatrix} \mathbf{f}_a(\mathbf{q}, \dot{\mathbf{q}}) \\ \mathbf{f}_p(\mathbf{q}, \dot{\mathbf{q}}) \end{bmatrix} + \begin{bmatrix} \mathbf{G}_a(\mathbf{q})\,\mathbf{u} \\ \mathbf{0} \end{bmatrix} \quad \begin{matrix} \}\dim_u = \dim_{qa} \\ \}\dim_{qp} \end{matrix} \Bigg\} \dim_q$$

$$\mathbf{\Phi}^d(\mathbf{q}) = \mathbf{0} \qquad \}\dim_{task}$$

Unknowns: general coordinates **q** and control inputs **u** : $\dim_q + \dim_u$

Scalar equations: total number is $\dim_q + \dim_{task}$

In the case $\dim_u = \dim_{task}$: unique solution exists for **q** and **u**

In the case $\dim_u > \dim_{task}$: no unique solution (spatial case…), optimization techniques may be needed like minimal kinetic energy, etc. …

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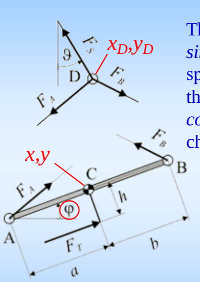
Redundant set of coordinates



The use of general coordinates may lead to *singularities* (e.g., spherical coordinates in the spatial case…), and also, the structure (**M(q)**) of the equations can be *complicated*, so instead of general coordinates **q**, choose the *redundant (natural) coordinates*:

$$\mathbf{z} = [x, y, \varphi, x_D, y_D]^{\mathrm{T}}$$

$\mathbf{F}_A = \lambda_A(\mathbf{r}_D - \mathbf{r}_A)$

$\mathbf{F}_B = \lambda_B(\mathbf{r}_D - \mathbf{r}_B)$

λ_A, λ_B: stiffness control – $u_{1,2}$

$\mathbf{F}_T = F_T[\cos\varphi \; \sin\varphi]^{\mathrm{T}}$ F_T: control force – u_3

$\mathbf{F}_S = -\lambda \mathbf{r}_D$ λ: Lagrange multiplier of ideal constraining force F_S

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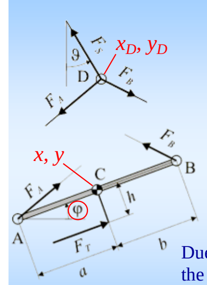
Solution of the direct task



$$J_C\ddot{\varphi} + (a\lambda_A - b\lambda_B)(x - x_D)\sin\varphi - (a\lambda_A - b\lambda_B)(y - y_D)\cos\varphi - F_T h = 0,$$

$$m\ddot{x} + (\lambda_A + \lambda_B)(x - x_D) - (F_T + a\lambda_A - b\lambda_B)\cos\varphi = 0$$

$$m\ddot{y} + (\lambda_A + \lambda_B)(y - y_D) - (F_T + a\lambda_A - b\lambda_B)\sin\varphi + mg = 0$$

$$(a\lambda_A - b\lambda_B)\cos\varphi + (\lambda_A + \lambda_B + \lambda)x_D - (\lambda_A + \lambda_B)x = 0$$

$$(a\lambda_A - b\lambda_B)\sin\varphi + (\lambda_A + \lambda_B + \lambda)y_D - (\lambda_A + \lambda_B)y = 0$$

$$x_D^2 + y_D^2 - l^2 = 0 \qquad \text{(DAE)}$$

Due to the selection of the redundant coordinates, the (nonlinear) algebraic part can be solved for λ, x_D and y_D in closed form,

then ODEs solved for x, y and φ for any given $\mathbf{u}(t) = (\lambda_A(t)\; \lambda_B(t)\; F_T(t))^{\mathrm{T}}$

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Application of computed torque method

First, the control inputs λ_A, λ_B and F_T are calculated based on the desired trajectory given by the scalar functions: x^d, y^d, φ^d.

This can be solved in closed form, again, in 2 steps:

$$x_D^d = x_D(x^d, y^d, \varphi^d, \ddot{x}^d, \ddot{y}^d, \ddot{\varphi}^d); \quad y_D^d = y_D(x^d, y^d, \varphi^d, \ddot{x}^d, \ddot{y}^d, \ddot{\varphi}^d);$$

Then the control inputs $\mathbf{u} = [\lambda_A \;\; \lambda_B \;\; F_T]^{\mathrm{T}}$ come from

$$\mathbf{Au} + \mathbf{b} = \mathbf{0}; \quad \mathbf{A} = \mathbf{A}(x^d, y^d, \varphi^d, x_D^d, y_D^d)$$

$$\mathbf{b} = [\ddot{\varphi}^d \;\; \ddot{x}^d \;\; \ddot{y}^d - g]^{\mathrm{T}}$$

Additionally, a closed loop linear controller is applied with the feedback for the active general coordinates $\mathbf{q}_a$:

$$\mathbf{q}_a = [x \;\; y \;\; \varphi] \qquad \mathbf{u}_{err} = \mathbf{K}_P(\mathbf{q}_a^d - \mathbf{q}_a) + \mathbf{K}_D(\dot{\mathbf{q}}_a^d - \dot{\mathbf{q}}_a)$$

$$\mathbf{q}_a^d = [x^d \;\; y^d \;\; \varphi^d] \qquad \mathbf{u}_{control} = \mathbf{u} + \mathbf{u}_{err}$$

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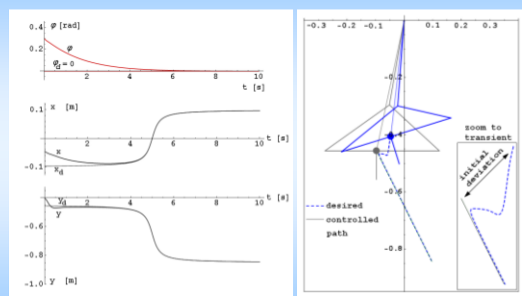
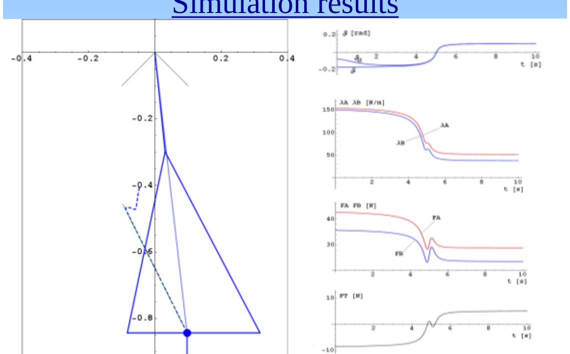
Desired motion and its perturbation



Simulation results



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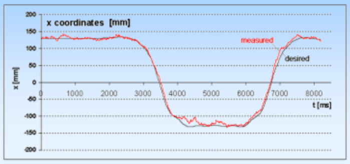
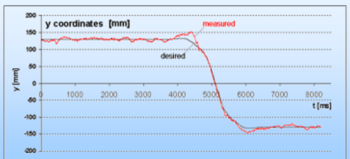
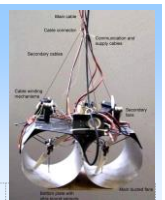
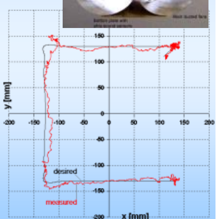
Prototype #1 experiments

video







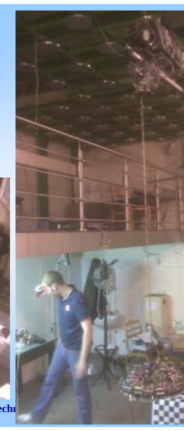


Prototype #2 experiments

video video video

Prototype #3 experiments

video video video video video



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Conclusion – Don't give up

- the appropriate choice of coordinates can simplify the structure of the equations of motion and can avoid singularities
- redundant number of coordinates may increase the size of the mathematical model but can simplify its solution
- the otherwise undesirable swinging of the manipulator can be utilized to achieve fast trajectory following

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• Lund University • Fraunhofer IPK
• Democritus University of Thrace • University of Reading
• Robosoft SA • Robotnik Automation SLL

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Conclusion #2 – never give up

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