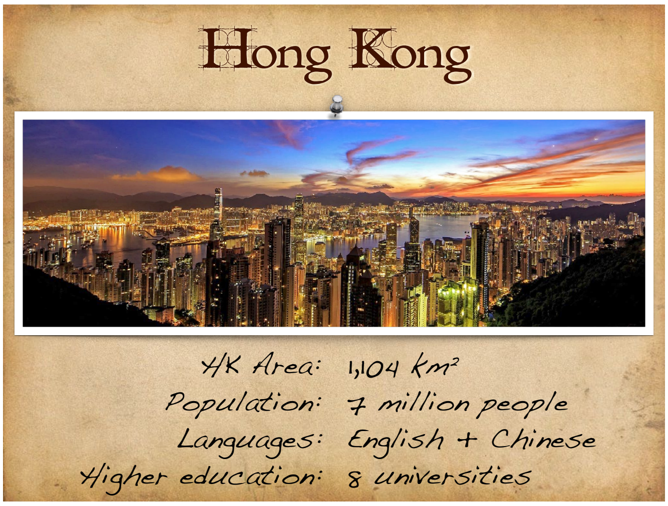
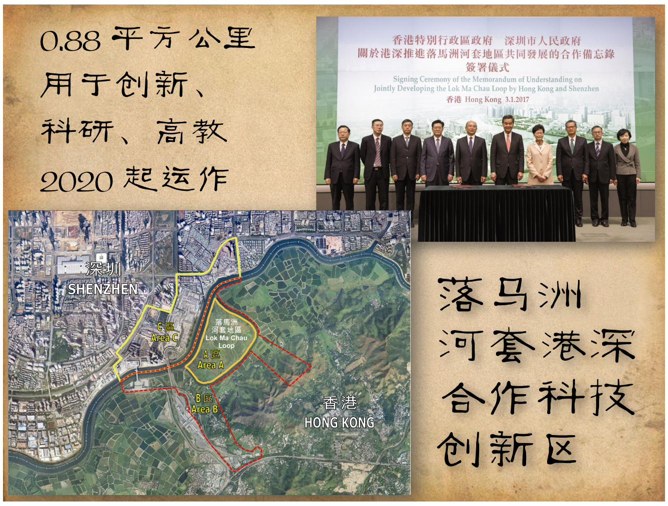

CUHK
- Establishment: 1963
- Campus: 1.37 km²
- 8 faculties
- 70 major programs
- 1,619 faculty members
- 20,147 students, 20% PGS

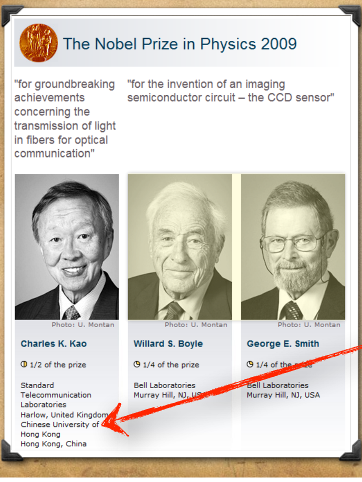

~2,146 undergraduates
~1,062 postgraduates
122 faculty members
26 IEEE Fellows


Hong Kong
HK Area: 1,104 km²
Population: 7 million people
Languages: English + Chinese
Higher education: 8 universities


0.88 平方公里
用于创新、
科研、高教
2020 起运作
香港特別行政區政府 深圳市人民政府
關於港深推進落馬洲河套地區共同發展的合作備忘錄
簽署儀式
Signing Ceremony of the Memorandum of Understanding on
Jointly Developing the Lok Ma Chau Loop by Hong Kong and Shenzhen
香港 Hong Kong 3.1.2017
深圳
SHENZHEN
Area C
Loh Ma Chau Loop
Area A
Area B
香港
HONG KONG
落马洲
河套港深
合作科技
创新区


机器人控制的现状、
挑战和机遇
孟庆虎


CUHK+HK Science Park




Dr. **Charles K. Kao**

Founding Chairman

of the

Electronic Engineering

Department

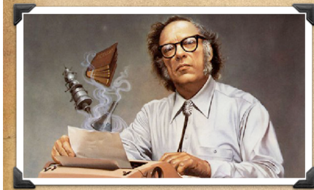
at the

Chinese University

of

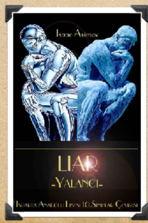
Hong Kong

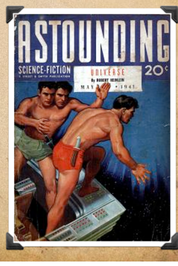
# The Term "Robotics": 1941



the May 1941 issue of *Astounding Science- Fiction*

Isaac Asimov used the word Robotics in his short SF story, *Liar!*, published in



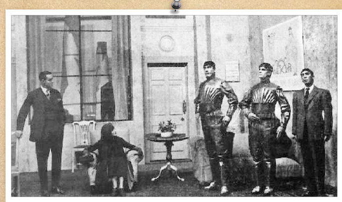



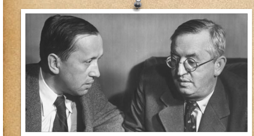

# HK UGC Results of the Research Assessment Exercise 2014

| Cost Centre | | Institution | Number of eligible staff | Percentage of research activity judged to meet the standard of : | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | 4 star | 3 star | 2 star | 1 star | unclassified |
| 18 | electronic engineering | CityU | 52 | 4 | 44 | 41 | 11 | 0 |
| | | HKBU | -- | -- | -- | -- | -- | -- |
| | | LU | -- | -- | -- | -- | -- | -- |
| | | CUHK | 36 | 21 | 42 | 31 | 2 | 4 |
| | | HKIEd | -- | -- | -- | -- | -- | -- |
| | | PolyU | 27 | 5 | 41 | 37 | 10 | 7 |
| | | HKUST | 40 | 16 | 58 | 24 | 1 | 1 |
| | | HKU | 36 | 7 | 47 | 35 | 6 | 5 |
| | | Sector-wide | 191 | 10 | 47 | 34 | 6 | 3 |

# The Term "Robota": 1920

Karel Čapek and his brother, Josef Čapek.



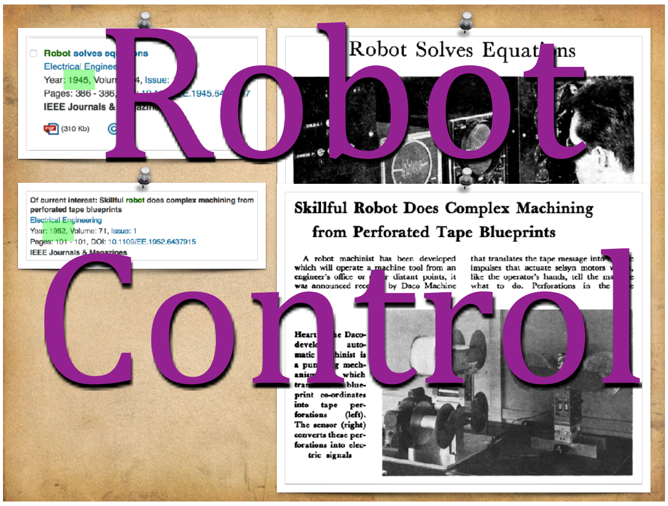


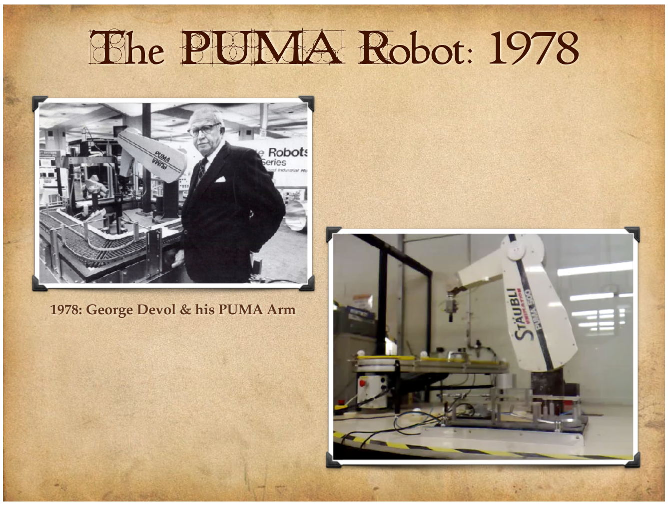
The 1920 play R.U.R. (Rossum's Universal Robots)

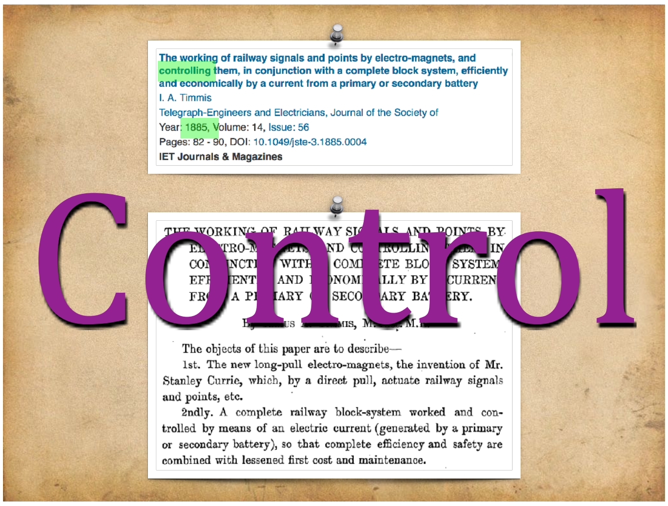
QS 2016 World University Ranking
========
Electrical/ Electronic Engineering Programs

| | | |
|---|---|---|
| 20 | 82.9 | The Chinese University of Hong Kong (CUHK) |
| 22 | 82.5 | The University of Hong Kong |
| 23 | 82.4 | National Taiwan University (NTU) |
| 23 | 82.4 | University of Michigan |
| 25 | 82.3 | The Hong Kong University of Science and Technology |
| 26 | 82.2 | Princeton University |
| 27 | 82.0 | Carnegie Mellon University |
| 27 | 82.0 | University of Toronto |

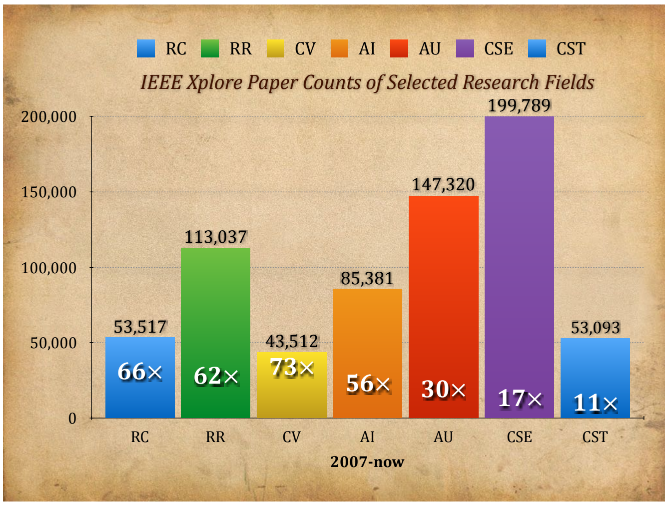
# A Brief History on Industrial Robot Control

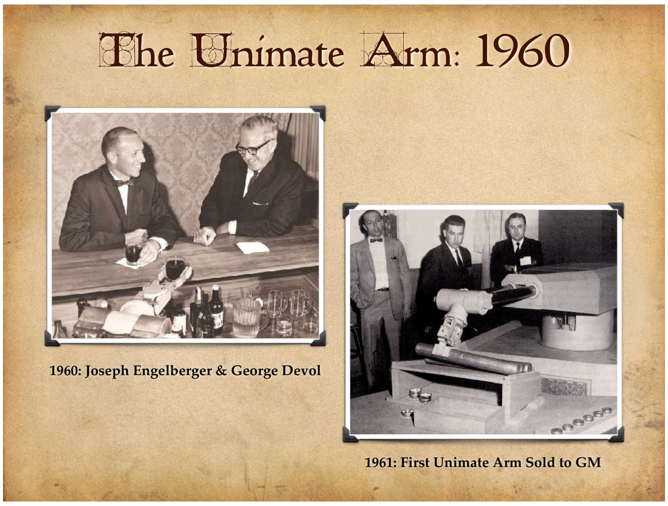

Robot
Control
Skillful Robot Does Complex Machining from Perforated Tape Blueprints
IEEE Journals & Magazines


The PUMA Robot: 1978
1978: George Devol & his PUMA Arm


The working of railway signals and points by electro-magnets, and controlling them, in conjunction with a complete block system, efficiently and economically by a current from a primary or secondary battery
I. A. Timmis
Telegraph-Engineers and Electricians, Journal of the Society of
Year: 1885, Volume: 14, Issue: 56
Pages: 82 - 90, DOI: 10.1049/jste-3.1885.0004
IET Journals & Magazines
Control
The objects of this paper are to describe—
1st. The new long-pull electro-magnets, the invention of Mr. Stanley Currie, which, by a direct pull, actuate railway signals and points, etc.
2ndly. A complete railway block-system worked and controlled by means of an electric current (generated by a primary or secondary battery), so that complete efficiency and safety are combined with lessened first cost and maintenance.


The Stanford Arm: 1969
1969: Victor Scheinman's Stanford Arm
1968: Victor Scheinman & his SAIL Arm


RC RR CV AI AU CSE CST
IEEE Xplore Paper Counts of Selected Research Fields
200,000
150,000
100,000
50,000
0
53,517
66×
113,037
62×
43,512
73×
85,381
56×
147,320
30×
199,789
17×
53,093
11×
RC RR CV AI AU CSE CST
2007-now


The Unimate Arm: 1960
1960: Joseph Engelberger & George Devol
1961: First Unimate Arm Sold to GM

# Robot Manipulator Dynamics

Robot manipulator dynamics:

$$M(\Theta)\ddot{\Theta} + V(\Theta, \dot{\Theta}) + G(\Theta) = \tau$$

where

$M \in R^{n\times n}$, a symmetric, PD mass matrix

$V \in R^{n\times 1}$, a vector containing all the velocity terms

$G \in R^{n\times 1}$, a vector containing gravity term

$\tau \in R^{n\times 1}$, the joint torque vector

$\Theta \in R^{n\times 1}$, the joint position vector

$n$ is the degree of freedom of the robot

Obviously, it is a second-order non-linear matrix equation.

# PD Control

Objective: $\Theta_d = \dot{\Theta}_d = \ddot{\Theta}_d = 0$

Dynamics: $M(\Theta)\ddot{\Theta} + V(\Theta, \dot{\Theta}) + G(\Theta) = \tau$

Control: $\tau = K_p(\Theta_d - \Theta) + K_v(\dot{\Theta}_d - \dot{\Theta}) = -K_p\Theta - K_v\dot{\Theta}$

Lyapunov function: $V = \frac{1}{2}\dot{\Theta}^T M(\Theta)\dot{\Theta} + \frac{1}{2}\Theta^T K_p \Theta + \phi(\Theta)$

and we then have: $\dot{V} = -\dot{\Theta}^T K_v \dot{\Theta} < 0$

and we then have: $\dot{\Theta} = 0 \Rightarrow \ddot{\Theta} = 0$, from the s.s. analysis,

$$K_p\Theta + G(\Theta) = 0 \Rightarrow \Theta_{ss} = -K_p^{-1}G(\Theta) \propto -\frac{1}{K_p}$$

Smaller $\Theta_{ss}$ requires larger $K_p$ (larger capacity motors)!

# Research on Robot Control

# Example of Regressor Dynamics

Example: For the 2 DOF robot shown in the illustration,

$$\tau_1 = m_1 l_1^2\ddot{\theta}_1 + I_{zz1}\ddot{\theta}_1 + I_{zz2}\ddot{\theta}_1 + m_2 d_2^2\ddot{\theta}_1 + 2m_2 d_2\dot{\theta}_1\dot{d}_2 + m_1 l_1 g c_1 + m_2 d_2 g c_1$$

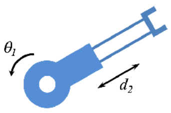
$$\tau_2 = m_2\ddot{d}_2 - m_2 d_2\dot{\theta}_1^2 + m_2 g s_1$$

$$\tau = \begin{bmatrix} \tau_1 \\ \tau_2 \end{bmatrix} = \begin{bmatrix} l_1^2\ddot{\theta}_1 + l_1 g c_1 & d_2^2\ddot{\theta}_1 + 2d_2\dot{\theta}_1\dot{d}_2 + d_2 g c_1 & \ddot{\theta}_1 & \ddot{\theta}_1 \\ 0 & \ddot{d}_2 - d_2\dot{\theta}_1^2 + g s_1 & 0 & 0 \end{bmatrix} \begin{bmatrix} m_1 \\ m_2 \\ I_{zz1} \\ I_{zz2} \end{bmatrix}$$

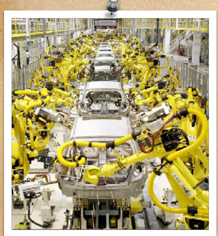
$$\Rightarrow \quad \tau = Y(\theta, \dot{\theta}, \ddot{\theta})\varphi$$

$$\Rightarrow \quad Y(\theta, \dot{\theta}, \ddot{\theta}) = \begin{bmatrix} l_1^2\ddot{\theta}_1 + l_1 g c_1 & d_2^2\ddot{\theta}_1 + 2d_2\dot{\theta}_1\dot{d}_2 + d_2 g c_1 & \ddot{\theta}_1 & \ddot{\theta}_1 \\ 0 & \ddot{d}_2 - d_2\dot{\theta}_1^2 + g s_1 & 0 & 0 \end{bmatrix}$$

$$\& \quad \varphi = \begin{bmatrix} m_1 \\ m_2 \\ I_{zz1} \\ I_{zz2} \end{bmatrix}$$




# Industrial Robot Control



# Robot Manipulator Dynamics

The robot dynamics:

$$M(\Theta)\ddot{\Theta} + V(\Theta, \dot{\Theta}) + G(\Theta) = \tau$$

can be expressed as a linear regressor equation as follows:

$$M(\Theta)\ddot{\Theta} + V(\Theta, \dot{\Theta}) + G(\Theta) = Y(\Theta, \dot{\Theta}, \ddot{\Theta})p$$

where

$Y(\Theta, \dot{\Theta}, \ddot{\Theta}) \in R^{n\times m}$, is a known, regressor matrix

$p \in R^{m\times 1}$, a vector of all the dynamics parameters

$m$ is the number of robot dynamics parameters

# Implementable Adaptive Control

Dynamics: $M(\Theta)\ddot{\Theta} + V(\Theta,\dot{\Theta}) + G(\Theta) = \tau$

Control: $\tau = \hat{M}(\Theta)\ddot{\Theta}^* + \hat{V}(\Theta,\dot{\Theta}) + \hat{G}(\Theta) = \hat{Y}(\Theta,\dot{\Theta},\ddot{\Theta}^*)\hat{\rho}$

where $\ddot{\Theta}^* = \ddot{\Theta}_d + K_v\dot{E} + K_pE$ and $E = \Theta_d - \Theta$

Lyapunov function: $V = E^T PE + \tilde{\rho}^T\Gamma^{-1}\tilde{\rho}$

and we then have: $\dot{V} = -E^T QE, Q > 0$

and with the parameter adaptation law defined as

$$\dot{\hat{\rho}} = -\Gamma Y^T(\Theta,\dot{\Theta},\ddot{\Theta})\hat{M}^{-1}(\Theta)B^T PE$$

The above offers a practical and stable robot adaptive control!

# Martin Buehler on SDU Robdog

# Slotine-Li Adaptive Control*

Dynamics: $M(\Theta)\ddot{\Theta} + V(\Theta,\dot{\Theta}) + G(\Theta) = \tau$

Control: $\tau = \hat{M}(\Theta)\ddot{\Theta}_r + \hat{V}(\Theta,\dot{\Theta})\dot{\Theta}_r + \hat{G}(\Theta) - Ks$

where $s = \dot{\Theta} - \dot{\Theta}_r$ and $\dot{\Theta}_r = \dot{\Theta}_d + \Lambda(\Theta_d - \Theta)$

Lyapunov function: $V = \frac{1}{2}s^T M(\Theta)s + \tilde{\rho}^T\Gamma^{-1}\tilde{\rho}$

and we then have: $\dot{V} = -\lambda s^T M(\Theta)s < 0$

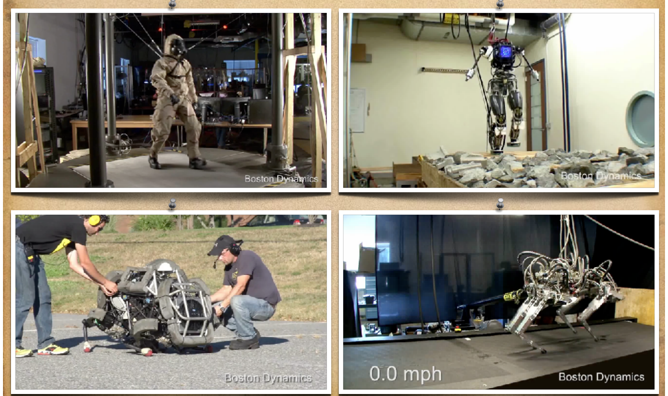
and with the parameter adaptation law defined as

$$\dot{\hat{\rho}} = -\Gamma Y^T(\Theta,\dot{\Theta},\dot{\Theta}_r,(\ddot{\Theta}_r - \lambda s))s$$

The above offers a (theoretical) stable robot adaptive control!

* JE Slotine and W Li, "Adaptive manipulator control: a case study," in Proc. of *IEEE ICRA 1987*, pp. 1392-1400.

# Boston Dynamics Robots




# PD plus Gravity Compensation

Objective: $\Theta_d = c \Rightarrow \dot{\Theta}_d = \ddot{\Theta}_d = 0$

Dynamics: $M(\Theta)\ddot{\Theta} + V(\Theta,\dot{\Theta}) + G(\Theta) = \tau$

Control: $\tau = K_pE - K_v\dot{\Theta} + G(\Theta)$ where $E = \Theta_d - \Theta$

Lyapunov function: $V = \frac{1}{2}\dot{\Theta}^T M(\Theta)\dot{\Theta} + \frac{1}{2}E^T K_pE$

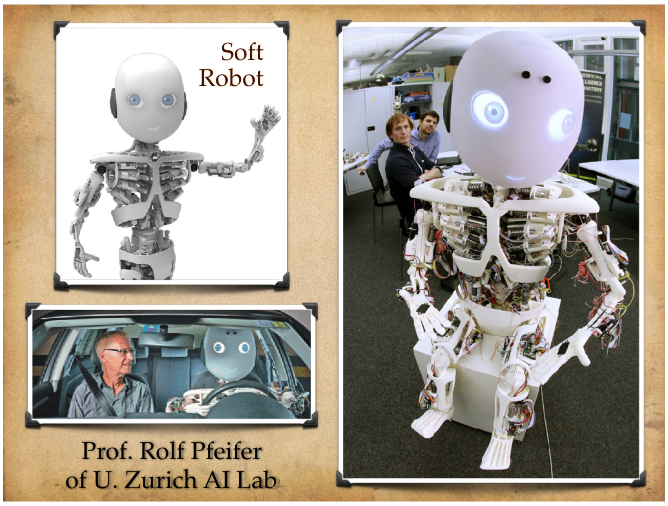
and we then have: $\dot{V} = -\dot{\Theta}^T K_v\dot{\Theta} < 0$

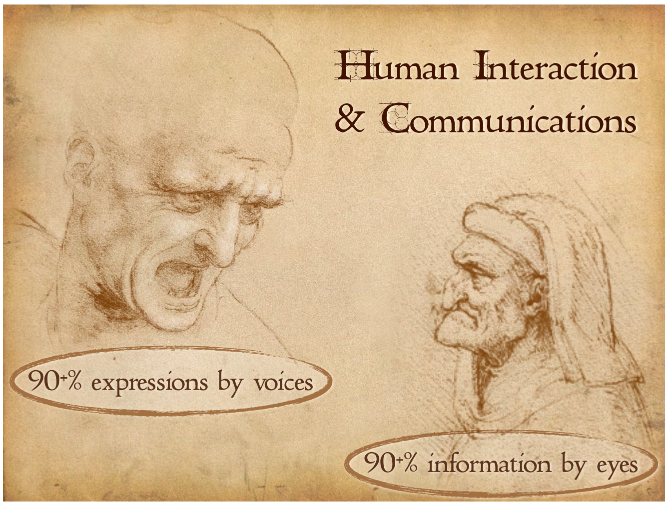
and we then have: $\dot{\Theta} = 0 \Rightarrow \ddot{\Theta} = 0$, from the s.s. analysis,

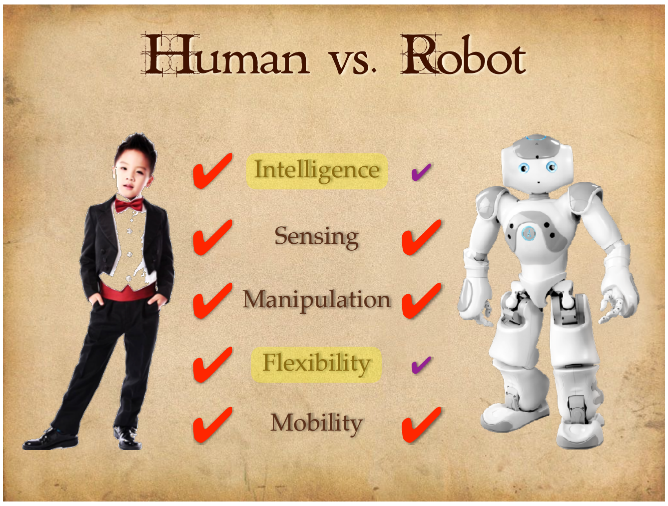
$$K_pE = 0 \Rightarrow E = 0 \Rightarrow \Theta = \Theta_d$$

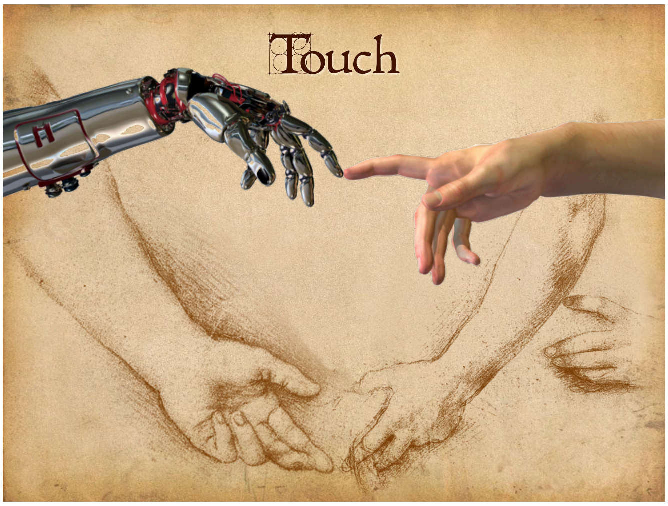
With gravity compensation, no ss error, but require $G(\Theta)$!

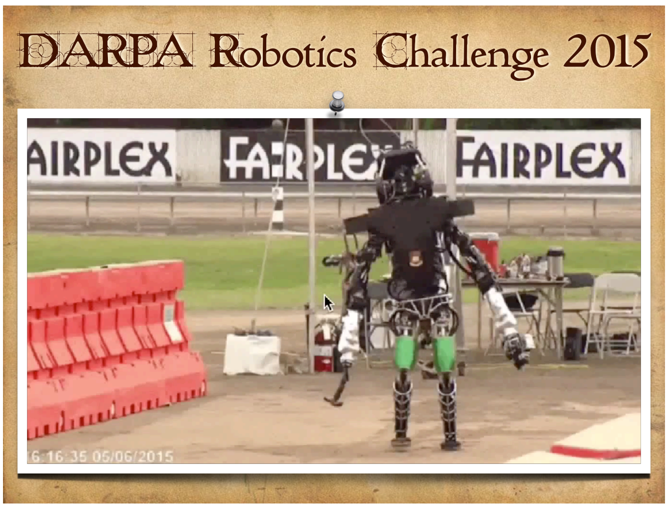
# State-of-the-Art Robots, Challenges & Solutions

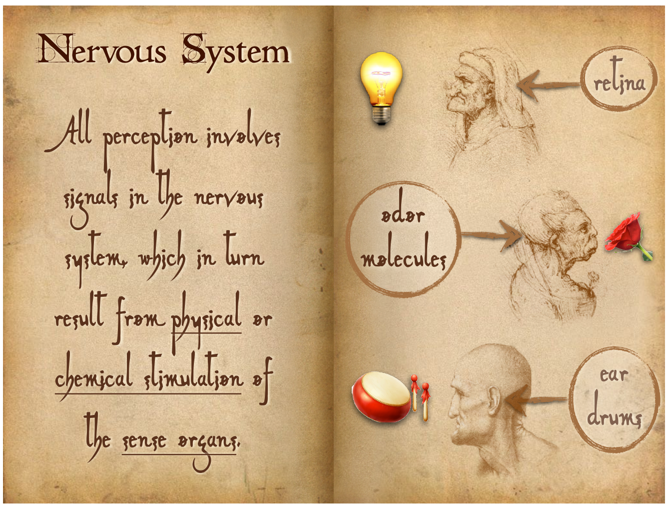

Soft
Robot
Prof. Rolf Pfeifer
of U. Zurich AI Lab


Human Interaction
& Communications
90+% expressions by voices
90+% information by eyes


Human vs. Robot
Intelligence
Sensing
Manipulation
Flexibility
Mobility


Touch


DARPA Robotics Challenge 2015

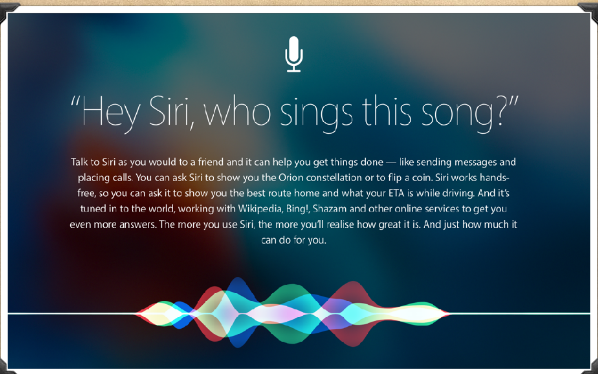

Nervous System
All perception involves signals in the nervous system, which in turn result from physical or chemical stimulation of the sense organs.
retina
odor molecules
ear drums

# Acknowledgement: My Group

# Interactive Smart Office Robot



# AI: Apple Siri




# Thank You!

My sincere gratitude to all of my students and research associates, past and present, for their inspiration and contributions to this talk!