Proseminar Roboter und Aktivmedien

Climbing robots achievements and challenging

Lecturer

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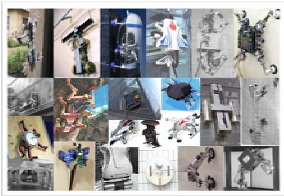

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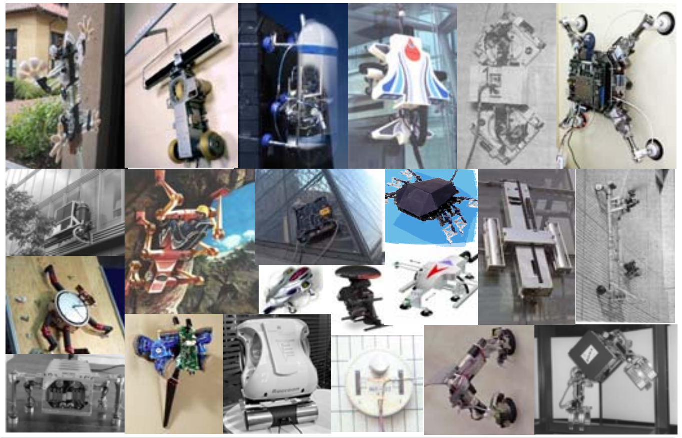

Outline of today's lecture

- What is a climbing robot?
- Review of climbing robots
  - Classification
  - Challenging issues
- Introduction to three kinds of climbing prototypes
  - Sky Cleaner family
  - A modular climbing caterpillar
  - Gecko climbing robot
- Conclusions

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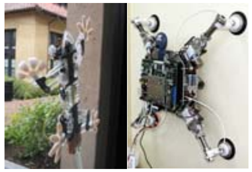
What is a climbing robot

- A special robot
- A kind of mobile robot
- Works and moves vertically on targets







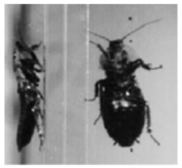
Research on climbing mechanisms

- Trunk kinematics


Other example

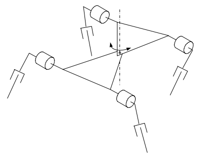
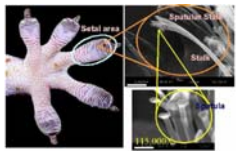
Research on climbing mechanisms

- Multiple-legged kinematics




Research on climbing mechanisms

- Gecko

Lecture material

- ***The 6th,7th,8th, and 9th International Conference on Climbing and Walking Robots and their Supporting Technologies for Mobile Machines, CLAWAR 2003-2006.***
- ***A Novel Modular Climbing Caterpillar Using Low-frequency Vibrating Passive Suckers***, H. Zhang, J. Gonzalez-Gomez, S. Chen, W. Wang, R. Liu, D. Li, J. Zhang, Proceeding of 2007 IEEE/ASME International Conference on Advanced Intelligent Mechatronlics, ETH Zurich , Switzerland, 4 - 7 Sept.2007.
- ***Sky Cleaner -A Real Pneumatic Climbing Robot for Glass-Wall Cleaning***, H. Zhang, J. Zhang, W. Wang, R. Liu, G. Zong, IEEE Robotic & Automation Magazine, Vol.13, No.1,2006, pp.32-41.
- ***Service Robotic Systems for Glass Curtain Walls Cleaning on the High-rise Buildings***, H. Zhang, D. Westhoff, J. Zhang, G.Zong, Proceeding of ISR2006& ROBOTIK2006.

Web links on climbing robots

- **IEEE Robotics and Automation Society(RAS)**
  - http://www.ncsu.edu/IEEE-RAS
- **Clawar**
  - http://www.clawar.org
- **Walking machine**
  - http://www.walking-machines.org/
- **European Robotics research Network (EURON)**
  - http://www.euron.org/
- **TAMS group**
  - http://tams-www.informatik.uni-hamburg.de/people/hzhang/projects/index.php

Climbing robot technology

- The last decade has seen an increasing interest in developing and employing climbing mobile robots for
  - *Industrial inspection;*
  - *Conducting surveillance;*
  - *Urban search and rescue;*
  - *Building maintenance;*
  - *Inspired research.*
- Two important issues for climbing robots
  - *Attachment principles for climbing robots*
  - *Kinematics of climbing prototypes*

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Climbing robots classification

- According to the attachment principles
  - Electromagnetic force
  - Molecular force
  - Mechanical force
  - Vacuum
- According to kinematics
  - Sliding frame robot;
  - Legged robot ;
  - Wheeled robot and chain-tracks
- According to applications
  - Industrial inspection;
  - Urban search and rescue;
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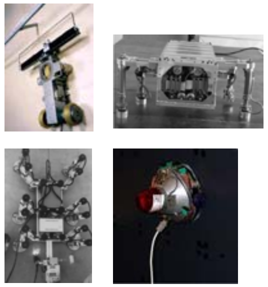
Electromagnetic force

- Electromagnetic force is not suitable for general climbing robots because it only works on ferromagnetic surfaces.
- Even if the adhesion is reliable and easy to control, actuating the electromagnet still requires a big and heavy power supply.

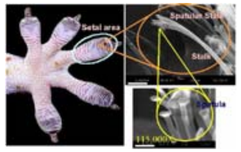


=>impossible to apply on light-weight climbing robots except in some special cases

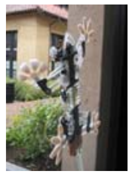
Other examples

Molecular force

- With the development of nanotechnology, molecular force has become a promising reliable attachment principle for climbing from the technical point of view.

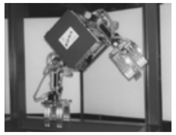


- However, the benefits of this novel adhesive principle are offset by high manufacturing costs and difficulties. Based on the current level of technology, real industrial application is still some way off.



Mechanical force

- Grippers are relatively prevalent. Usually climbing robots based on this attachment method work in a specialized environment such as metal-based buildings.




- A propeller is another way to provide the mechanical attachment force. It is very light, but the level of noise generated is too high.


Vacuum

- Actuated by electrical motors in its negative pressure chamber, the climbing robot can move on the wall flexibly and continuously.

- The vacuum in the suckers is usually established by vacuum ejectors or vacuum pumps.

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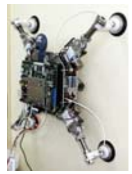
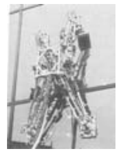
Kinematics of climbing robots

- Currently there are several different kinds of kinematics for motion on vertical surfaces:
  - *Multiple legs*
  - *Sliding frame*
  - *Wheeled and chain-track vehicle*

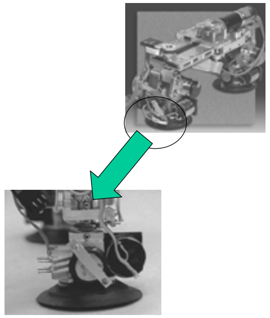







Two-legged climbing robot

- Miniature robot (cm^2): 52.5
- Lightweight: <500g
- Vacuum suction
- Move very slowly
- Without enough sensors on board



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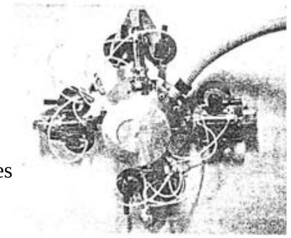
ROSTAM-III

- Weight: 4kg
- Negative pressure &Vacuum
- Move very slowly
- Have the ability of passing over obstacles



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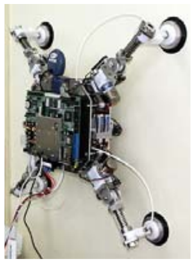
Legged climbing robot



Legged climbing robot example

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Kinematics of climbing robots

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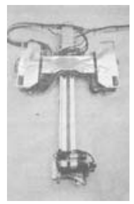

Kinematics of climbing robots

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  - *Multiple legs*
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Alicia robot (Catania, 2000)

- Dimension (cm^2): 160
- Weight: 2kg
- Negative pressure
- Cannot pass over obstacles

Customized glass-roof cleaning robots

- The RobuGLASS™ robot, developed by ROBOSOFT, is a 4-track platform moving along the external glass surface of the Louvre's Pyramid.
- Innovative technical solutions :
  - A suction system keeping the robot stuck to the surface while moving up and down, without any safety cable.
  - A remote control and autonomous navigation system, using sensors to track the window frames.
  - A light chassis, made of carbon fiber.
  - A redundant control and vacuum system, for safety.

RobuGLASS™ robot

http://www.robosoft.fr/eng/sous_categorie.php?id=1017

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Challenging

- Generally climbing robots are relatively large.
- Additionally, the intelligent technology in these climbing robots is not well developed.
- The reason for this situation is that in designing a new prototype, attention was too focused on attachment safety and climbing kinematics and dynamics.
- Normal problems in mobile technology.

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Mobile Robotics

A family of pneumatic climbing robots for glass wall cleaning

Lecturer

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  - Sky Cleaner 1
  - Sky Cleaner 2
  - Sky Cleaner 3
- Nonlinear control algorithms
- Conclusions

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Background of cleaning robots

Outer glass wall cleaning

Outer glass wall cleaning

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Benefits of the glass cleaning robot

- Realizes automatic cleaning of high- rise buildings, thus improving the technological level
- Saves the cost of installing expensive permanent gondola systems at the individual building.

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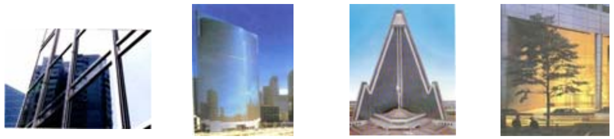
Study on Operation Targets



(a) *(b)* *(c)* *(d)*

- Exposed-frame glass curtain wall (shown in Fig (a));
- Semi-exposed-frame glass curtain wall (shown in Fig (b));
- Hidden-frame glass curtain wall (shown in Fig (c));
- Full glass curtain wall (shown in Fig (d));

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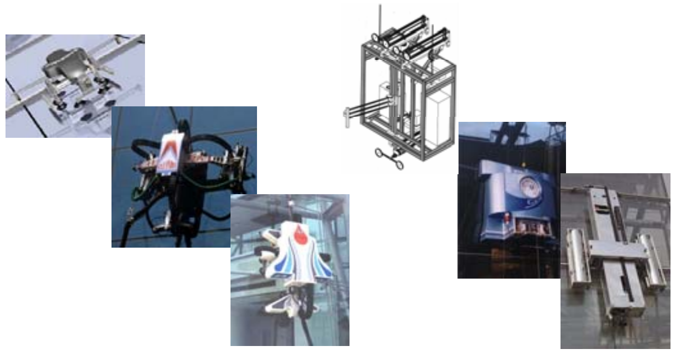
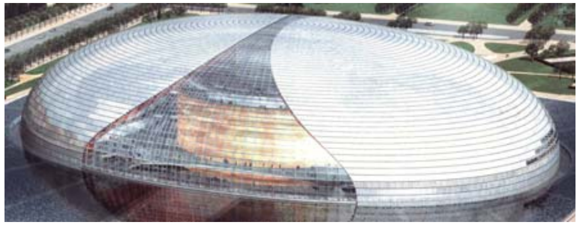
Cleaning robots for high-rising buildings



Cleaning target



Basic functions

- Safe and reliable attachment to the glass surface
- Movement covering all the working areas
- The ability of crossing window obstacles
- Enough intelligence for the discrimination of a variety of obstacle situations
- Working autonomously with the corresponding effective treatment
- Motion control function
- Friendly Graphical User Interface
- Efficient cleaning

Sky Cleaner Robots

1997

"Sky Cleaner-I"

1999

"Sky Cleaner-II"

2001

"Sky Cleaner-III"

2006

"Sky Cleaner-IV"

Why design pneumatic robots

- Advantage
  - Lightweight
  - Passive compliance, safer than driven by motors
- Disadvantage
  - Nonlinearities and low stiffness

Advantages of the pneumatic system

Items	Driven linear guidance units		
	Pneumatic		Electrical
	NORGREN	SMC	NEFF
Model	46140/400	MYC-400	WH50/400
F_{drive}(Kg)	75.0	75.0	67.0
M_X(NM)	39	19.6	16
M_Y(NM)	110	58.8	87
M_Z(NM)	110	19.6	50
Weight for linear unit(Kg)	4.9	8.9	6.16
Weight for actuator(Kg)	<1.0	<1.0	6.0
Connectors (Kg)	0.5	0.5	0.5
Total weight G_{drive} (Kg)	6.4	10.4	12.66
Power-to-weight ratio	11.72	7.21	5.29
Definition	$\text{Power-to-weight ratio} = \frac{F_{drive}}{G_{drive}}$		

A linear cylinder is 1-2 times lighter than a motor-driven linear-motion unit with similar specifications.

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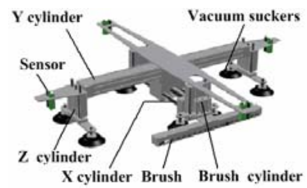
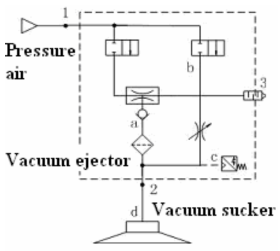
Sky cleaner 1

- The first robot for cleaning the glass roof of the Beijing Railway Station was designed before 2000.



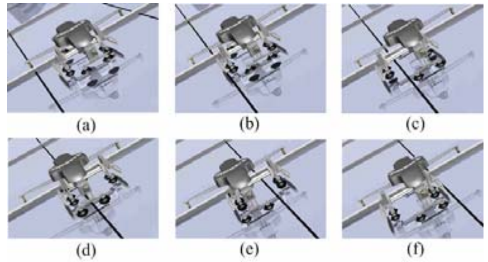
Sky cleaner 1

- A PC is used as a console on the ground, and the on-board controller includes PC104 and PLC.
- The PC104 computer is the core controller and in charge of the global intelligent control such as planning and identifying the sensor inputs.
- PLC is the assistant controller that collects the internal switch sensor signals and actuates all the solenoid valves.



Sky cleaner 1

- It cannot work on a vertical wall.
- Because it lacks a waist joint, it cannot correct the direction of motion.
- Cleaning efficiency is at only about 37.5 m^2/ hour.



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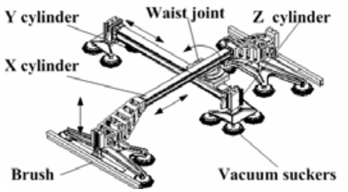
Sky cleaner 2

- The following project was aimed at developing a cost-effective, mobile robotic system for moving on vertical glass walls and high-quality cleaning of the surfaces of high-rise curtain walls.

Sky cleaner 2

- It features 16 suction pads
- A pair of cylinders provides both vertical and horizontal motion
- A specially designed waist joint gives a turning motion to the robot.



- *The robot is portable and cleaning efficiency is at about 75 m^2/ hour. But as considerable stress was laid on weight reduction, the stiffness is somewhat low so that there is a small distortion while cleaning.*

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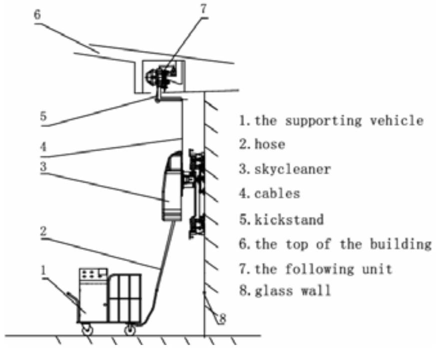
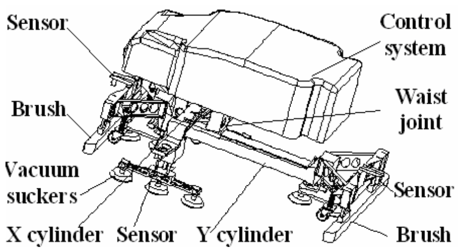
Sky cleaner 3

The robotic system



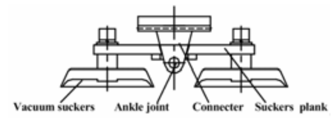
Sky cleaner 3



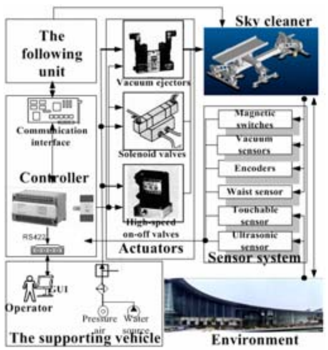
On opposite ends in the Y direction there are also four brush cylinders, which actuate the brushes up and down. An adaptive cleaning head is designed especially for effective, efficient and safe cleaning, equipped with a drainage collecting device.

Sky cleaner 3

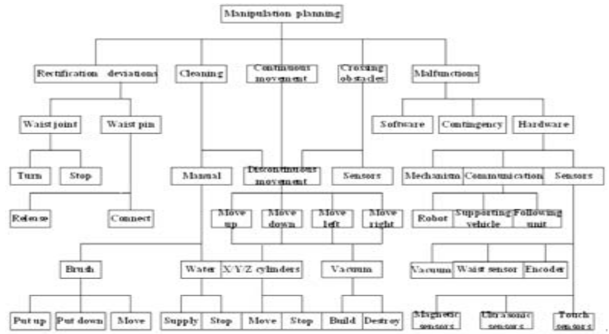
- In order to enable movement from one column of glass to another in the horizontal direction, an ankle joint gives a passive turning motion to the suckers.
- All mechanical parts are designed specifically and mainly manufactured in aluminum.



Control implementation



Software hierarchy



Some photos about cleaning in Shanghai

Conclusions

Type / Capability	Sky Cleaner 1	Sky Cleaner 2	Sky Cleaner 3
Target character	Glass wall 0°-45°	Glass wall 0°-90°	Glass wall 0°-90°(with < 2° angle)
Efficiency(m^2/8 hours)	**37.5**	**75**	**100-125**
Cross obstacles (mm^2): HeightxWidth	Window frame: 30x60	Window frame:30x60; Seal: -1x20	Window frame:10x60; Seal:-1x20
Weight (kg)	25	25	45
Body Mass(mm^3): LengthxWidthxHeight	935x900x320	1220x1340x370	1136x736x377
Supporting unit	Supporting vehicle	Supporting vehicle and following unit	Supporting vehicle and following unit
Water supply(L/hour)	50(reused)	50(reused)	50(reused)
Operators	1	1-2	1-2

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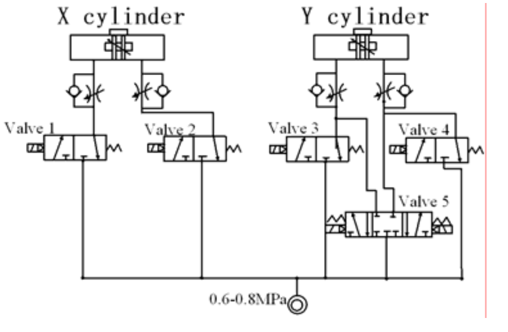
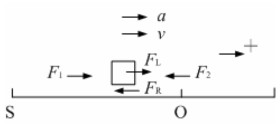
Schemes of the X and Y cylinders



Control model of the X cylinder



Object of a perfect position servo control algorithm :

If $|SO| \rightarrow 0$

Then $\left.\begin{array}{l} a \\ v \end{array}\right\} \rightarrow 0$

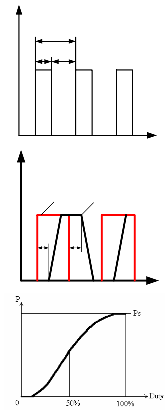
S: Start position of piston
O: Target position of piston
F_1, F_2: Left and right chamber forces on piston respectively
F_L: Load force
F_R: Friction force
a: Expectative acceleration
v: Velocity of piston

PWM

- The PWM (pulse width modulation) pneumatic position uses the controller to create a high frequency pulse signal to drive the on and off of high-speed solenoid valve. The duty (percentage of on-time to PWM period) on the valve will determine the output flow rate or pressure to the cylinder chamber.
- A typical PWM signal is shown in figure, where T is the PWM period, To is on-time. Because there exit electrical and mechanical delays on the valve, the pressure output of the valve is generally like the curve in the right figure. Where T_{od} is the delay time of on, T_{fd} is the delay time of off. Both the delay times are determined by the response time of the solenoid valve.

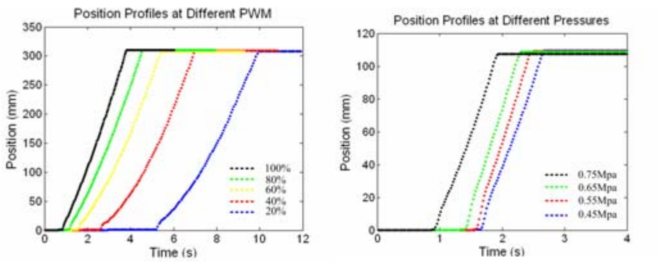
$$\tau = \frac{T_o}{T} \times 100\%$$

- The relationship between the duty of the valve and its output pressure is shown in last figure. The bigger the duty, the bigger the output pressure.



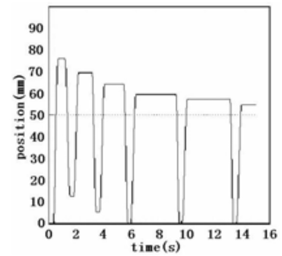
Characteristics of pneumatic system

- Characteristics of the pneumatic cylinders



Different pneumatic control algorithms

- Fuzzy PID for Sky Cleaner 1

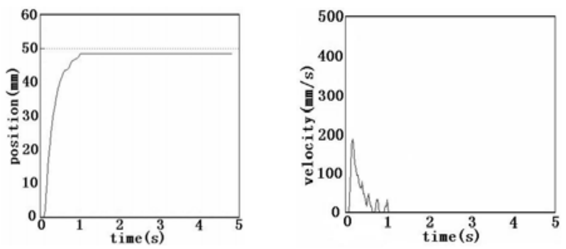


The position profile of the linear PID.

Other examples

Different pneumatic control algorithms

- Fuzzy PID for Sky Cleaner 1



50mm-movement position and velocity profiles of the fuzzy PID

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Different pneumatic control algorithms

- Fuzzy PID for Sky Cleaner 1

	X cylinder			*Y cylinder*		
No.	Desired position (mm)	errors (mm)	$\|e\|_{max}$	Desired position (mm)	errors (mm)	$\|e\|_{max}$
1	50.0	1.86		50.0	2.01	
2	50.0	2.48		50.0	1.54	
3	50.0	2.25	2.25	50.0	2.33	2.33
4	50.0	2.17		50.0	2.72	
5	50.0	1.98		50.0	0.96	

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Different pneumatic control algorithms

- Proportional control with mechanical brakes for Sky Cleaner 2

$$\tau = \begin{cases} 100 & k_p(x_d - x) \geq 100 \\ k_p(x_d - x) & 0 \leq k_p(x_d - x) \leq 100 \\ 0 & k_p(x_d - x) \leq 0 \end{cases}$$

Where k_p is proportional coefficient, x_d is the desired position, x is the current position. When the cylinder arrives at the desired position, the brake cylinders will mechanically stop it.

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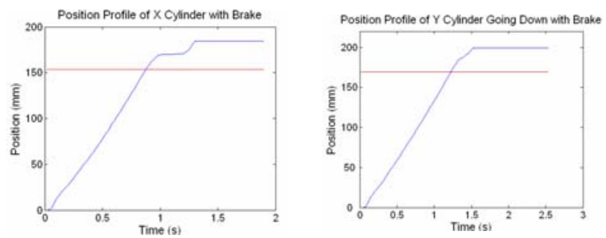
Different pneumatic control algorithms

- Proportional control with mechanical brakes for Sky Cleaner 2



Different pneumatic control algorithms

- for Sky Cleaner 2

	X cylinder			Y cylinder		
No.	Desired position (mm)	errors (mm)	$\|e\|_{max}$	Desired position (mm)	errors (mm)	$\|e\|_{max}$
1	30.0	1.09	1.36	30.0	1.60	1.60
2	30.0	1.129		30.0	1.51	
3	30.0	0.76		30.0	0.62	
4	30.0	1.36		30.0	1.28	
5	30.0	0.05		30.0	0.08	

Different pneumatic control algorithms

- Segment and Variable Bang-bang Controller for Sky Cleaner 3

Generally, the bang-bang controller for the pneumatic system is described with

$$U_i = -U_{MAX}(e_s) \quad i=1,2 \quad (1)$$

$$|e_s| \le \varepsilon \quad (2)$$

Segment and variable bang-bang controller

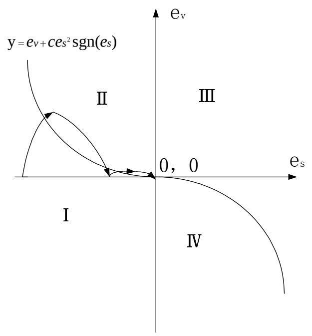
$$y = e_v + c e_s^2 \operatorname{sgn}(e_s) \quad (3)$$

$$U_i = -U_{MAX} \operatorname{sgn}(y) \quad i=1,2 \quad (4)$$

$$U_1 + U_2 = U_{MAX} \quad (5)$$

$$\sqrt{e_s^2 + e_v^2} \le \varepsilon \quad (6)$$

The phase plane

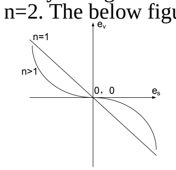


Conclusions and recommendations

- The construction function can be described with the following equation.

$$y = e_v + c e_s^n \operatorname{sgn}(e_s)^{\mathrm{mod}(\frac{n+1}{2})} \longrightarrow y = e_v + c e_s^2 \operatorname{sgn}(e_s)$$

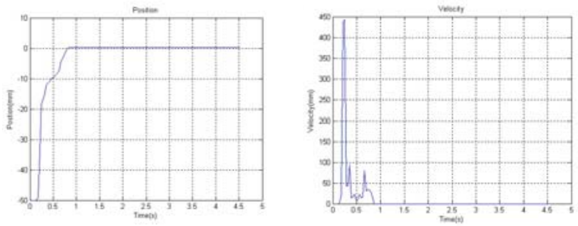
- The parameter n has an important influence on the position control. The velocity will increase considerably when n is reduced. At the same time, the stability of the control system gradually decreases. In this system, the parameter is set to n=2. The below figure shows the dependency of the y on the n.



Parameter C

- Parameter c is also important. The value should be suitable.

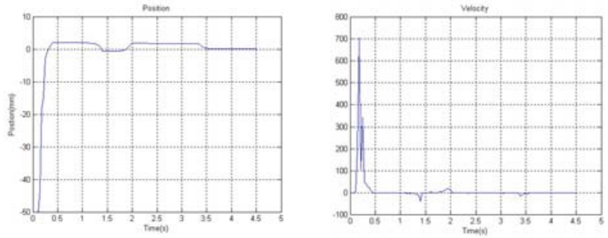
$$y = e_v + c e_s^{n} \operatorname{sgn}(e_s)^{\operatorname{mod}(\frac{n+1}{2})}$$



C=2

Parameter C

- When c is 8, the velocity is about 700mm/s but the system will take a long time to stabilize.

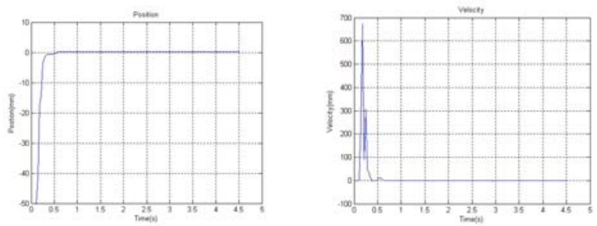


C=8

Conclusions and recommendations

- Here c is set to five for the realization.

$$y = e_v + c e_s^{n} \operatorname{sgn}(e_s)^{\operatorname{mod}(\frac{n+1}{2})}$$



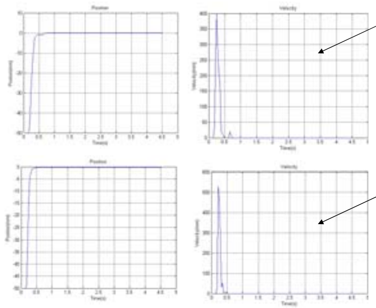
C=5

Conclusions and recommendations

- The pressure should be as high as possible.

P=5 bar

P=6.5 bar

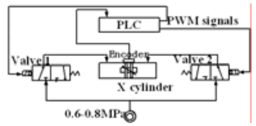


Different pneumatic control algorithms

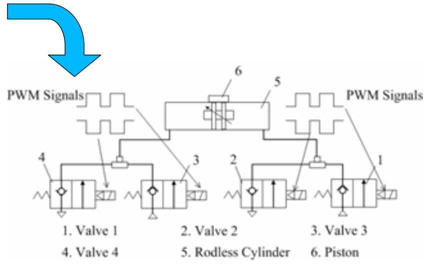
- Segment and Variable Bang-bang Controller for Sky Cleaner 3

No.	1	2	3	4	5	6	7	8	9	10
Condition	Po=6.5Mpa, C=5, e_b=10mm, Ts=35ms, ε_{max}=±0.5mm, n=10									
Desired position S(mm)	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0
Actual position Si(mm)	50.0	50.1	49.8	50.2	49.8	50.5	49.7	49.9	49.9	50.0
Average(mm)	$\bar{s} = \sum_{i=1}^{n} s_i / n = 49.99(mm)$									
σ (mm)	$\sigma = \sqrt{\sum_{i=1}^{n}(s_i - \bar{s})^2 / (n-1)} = 0.23(mm)$									
Position accuracy(mm)	$V_r = \pm 3\sigma = \pm 0.69(mm) < \pm 1(mm)$									

PWM-based cylinder driving system



Original Cylinder Driving System



Cylinder Driving System in "Sky Cleaner-IV"

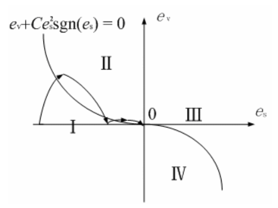
Basic variable bang-bang control algorithm

$$y = e_v + c e_s^2 \operatorname{sgn}(e_s)$$

$$U_i = -U_{MAX} \operatorname{sgn}(y) \qquad i=1,2$$

$$\sqrt{e_s^2 + e_v^2} \le \varepsilon$$

$y(e_v, e_s)$: Switch evaluation function
e_s: Position error
e_v: Velocity error
C: Undetermined plus constant
sgn( ): Sign function
Ui: Control signal
ε : Combined error index



Phase plane portrait of switch evaluation function

The shortcomings:

1. *Non-zero acceleration value when ε < limit value*
2. *The effect of friction is ignored*

F&A compensating control algorithm

$$\varepsilon > \varepsilon_{max} \begin{cases} y<0 \Rightarrow F_1>F_2,\ a>0 & \begin{cases} v \ge 0 \Rightarrow F_1 = (m|a|+F_R-F_L)/(1-p),\ F_2 = p F_1 \\ v < 0 \Rightarrow F_1 = (m|a|-F_R-F_L)/(1-p),\ F_2 = p F_1 \end{cases} \\ y \ge 0 \Rightarrow F_1<F_2,\ a<0 & \begin{cases} v \ge 0 \Rightarrow F_1 = (m|a|-F_R+F_L)/(1-p),\ F_2 = p F_1 \\ v < 0 \Rightarrow F_1 = (m|a|+F_R+F_L)/(1-p),\ F_2 = p F_1 \end{cases} \end{cases}$$

$$\Delta_1, \Delta_2$$

$$\varepsilon \le \varepsilon_{max} \Rightarrow \begin{matrix} F_1 = F_2 = F_{max} & (t \le T) \\ F_1 = \Delta_1,\ F_2 = \Delta_2 & (t \ge T) \end{matrix}$$

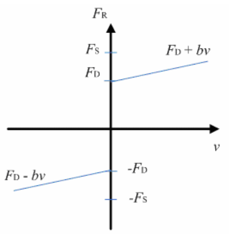
m: Mass of piston and load ; ε : Combined error index; ε_{max}: Limit of error
p(<1): Back pressure coefficient to enhance the cylinder rigidity;
F_{max}: Pushing force under air pressure;

Discrimination of F_R

$$F_R = F_F + bv$$

$$F_F = \begin{cases} F_S & (v = 0) \\ F_D \bullet \mathrm{sgn}(v) & (v \neq 0) \end{cases}$$

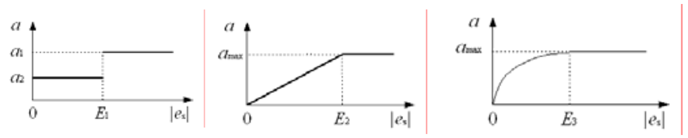
F_F: Gross friction on piston
Fs: Breakdown friction of cylinder
b: Damp coefficient;
v: Velocity of piston;
sgn (v): Sign function
F_D: Dynamic friction



Friction physical model of cylinder

NORGREN, M/46132/M/300
F_L = 7.2Kgf, F_S≈120N, F_D≈120N, b≈200Ns/m

Determination of expectative acceleration a



$$a = \begin{cases} a_{max} & (|e_s| \geq E_1) \\ a_1 & (E_1 > |e_s| \geq E_2) \\ 0 & (|e_s| < E_2) \end{cases}$$

Step function of a

$$a = \begin{cases} a_{max} & (|e_s| \geq E_2) \\ k|e_s| & (|e_s| < E_2) \end{cases}$$

Linear function of a

$$a = \begin{cases} a_{max} & (|e_s| \geq E_3) \\ (2a_{max} \arctan(10|e_s|/E))/\pi & (|e_s| < E_3) \end{cases}$$

Arc-tangent function of a

$E_1 = E_2 = |e_s|/3$; $E_3 = |e_s|/4$

Results of position servo of X cylinder

Results of position servo test for X cylinder

Testing condition	Air source pressure Po = 6Mpa; Distance: e_{max} = 148mm; C = 5, ε_{max} = 0.5, F_L = 300N, m = 32Kg	
Step function	Average value	146.85mm
	Average steady time	1.86s
	Variance analysis	1.36mm
	Repeating precision	±4.08mm
	Max overshoot	2.5mm
Linear function	Average value	147.24mm
	Average steady time	1.12s
	Variance analysis	0.53mm
	Repeating precision	±1.59mm
	Max overshoot	2.1mm
Arc-tangent function	Average value	148.14mm
	Average steady time	1.64s
	Variance analysis	0.32mm
	Repeating precision	±0.96mm
	Max overshoot	1.4mm

Outline of this part

- Background of cleaning robots
- Overview of Sky Cleaner family
  - Sky Cleaner 1
  - Sky Cleaner 2
  - Sky Cleaner 3
- Nonlinear control algorithms
- Conclusions

Conclusions

- Since 1996, our international group has been developed four Sky Cleaners fully pneumatic climbing robots for cleaning the glass-wall of high-rise buildings.
- Several non-linear algorithms for the cylinder's movement control are proposed and tested on Sky Cleaners.

Outline of today's lecture

- What is climbing robot?
- Review of climbing robots
  - Classification
  - Challenging issues
- Introduction to three kinds of climbing prototypes
  - Sky Cleaner family
  - A modular climbing caterpillar
  - Gecko climbing robot
- Conclusions

Mobile Robotics

A novel modular climbing caterpillar using low-frequency vibrating passive suckers

Lecturer

Dr. Houxiang Zhang

TAMS, Department of Informatics
University of Hamburg, Germany

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Outline of this part

- Our idea
- Overview of prototype design
- Low-frequency vibrating passive suckers
- Locomotion control
- Implementation
- Conclusions

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Our idea

- The modular approach allows us to build mobile robotic systems that are versatile, robust, come at a low cost and can be prototyped fast.
- We combine climbing techniques with a modular approach to realize a novel prototype as a flexible, wall climbing robotic platform featuring all locomotion capabilities.
- ***The emphasis for discussion is currently on the prototype design and rational testing of the novel system.***

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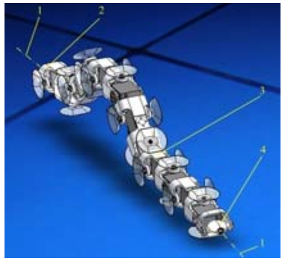
ZC-I modular climbing caterpillar

- Quick-to-assemble mechanical structure and low-frequency vibrating passive attachment principle.
- Active joints actuated by RC servos endow the connecting modules with the ability of changing shapes in two dimensions.
- Various locomotion capabilities will be achieved based on an inspired control model to produce rhythmic motion.



Picture taken from a 3D-animation of the planned robotic caterpillar in a variety of postures.

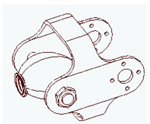
Overview of prototype design

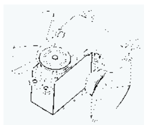
- The major challenges in designing: the smaller dimension and the ability to attach to the wall safely and move flexibly.
- Eleven cross-connected modules for moving.
- Only two kinds of modules: the head and tail module; the body module.
- The mechanical structure can be reconstructed and is flexible due to its similar modules and special connection joints.

Picture taken from a 3D-animation of the planned robotic caterpillar in a variety of postures.

Overview of prototype design (cont')

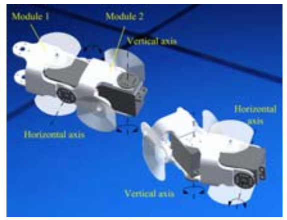
- Modules
  - The head and tail module consists of a CCD camera and mechanical shell with two pairs of ears. There is no embedded DOF so that it cannot move actively.
  - A body module consists of a shell with three pairs of ears, an RC servo and a pair of small passive suckers which are fixed to the shell.





Overview of prototype design (cont')

- Connecting
  - The driving servo is screwed to a pair of ears on Module 1; while the rotating plate of the servo is screwed to another pair of ears on Module 2 which is rotated by 90 degrees.
  - The connection between the two modules is completed by attaching the rotating plate to the servo again. In this way, the caterpillar is alternately assembled around the horizontal axis and vertical axis.



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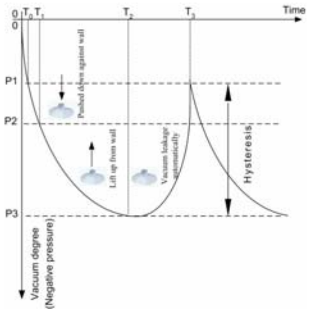
- Locomotion control
- Implementation
- Conclusions

Low-frequency vibrating passive suckers

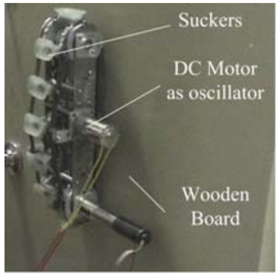
- Keep the merits and eliminate the shortcomings of normal active vacuum suckers
- Make it possible to avoid the usual heavy vacuum ejectors and realize an simple adsorption
- Improve the inspired technological level and flexibility of the locomotion capability

• *In principle*



Low-frequency vibrating passive suckers

- Rational experiment



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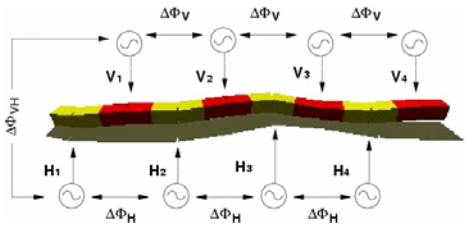
Locomotion control

- The sinusoidal generators produce very smooth movements and have the advantage of making the controller much simpler. Our model is described by the following equation .

$$y_i = A_i \sin(\frac{2\pi}{T} t + \phi_i) + O_i$$

- Where y_i is the rotation angle of the corresponding module; A_i is the amplitude; T is the control period; t is time; Φ_i is the phase; O_i is the initial offset.

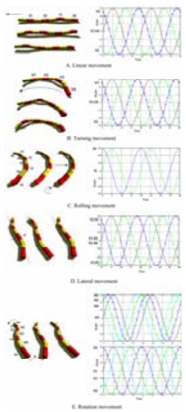
Locomotion control (cont')



- They are divided into horizontal and vertical groups, which are described as H_i and V_i respectively. Where i means the module number;
- $\Delta\Phi_V$ is the phase difference between two adjacent vertical modules;
- $\Delta\Phi_H$ is the phase difference between two adjacent horizontal modules;
- $\Delta\Phi_{HV}$ is the phase difference between two adjacent horizontal and vertical modules.

Locomotion control (cont')

Gate types	Parameters for sinusoidal generators	
Linear movement	A_{Vi} 0; A_{Hi}=O_{Vi} =0	$\Delta\Phi_V$=100-120, O_{Hi} 0
Turning movement		$\Delta\Phi_V$=100-120, O_{Hi}=0
Rolling movement	A_{Hi}, A_{Vi} 0; O_{Hi}=O_{Vi} =0	$\Delta\Phi_V$= $\Delta\Phi_H$=0, $\Delta\Phi_{VH}$=90
Lateral movement		$\Delta\Phi_V$= $\Delta\Phi_H$=100, $\Delta\Phi_{VH}$=0
Rotation movement		$\Delta\Phi_V$=120, $\Delta\Phi_H$=0, $\Delta\Phi_{VH}$=50



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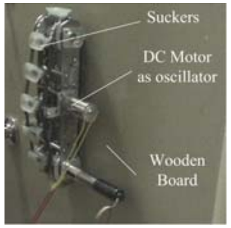
Implementation

- The implementation requires the following features: reliable attachment, light mechanical modules and realization of the movement. In order to reduce the time required for research, three features are implemented at the same time.



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Implementation (cont')

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Implementation (cont')

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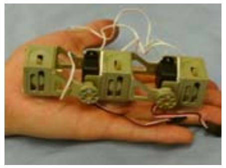

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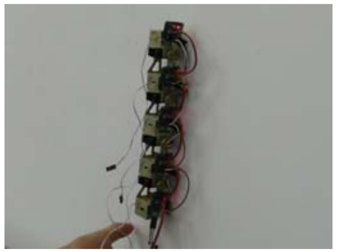
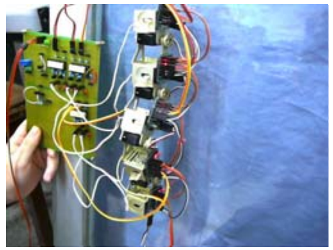
Implementation (cont')





Outline of this part

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Conclusions

- This part introduced a novel modular climbing caterpillar named ZC-I, which combines climbing techniques with the modular idea.
- The mechanical structure and the low-frequency vibrating passive attachment principle are introduced in detail.
- ZC-I features identical active joints actuated by RC servos which endow the connecting modules with the ability of changing shapes in two dimensions.
- A series of relative simulations and tests confirm our design principles described above.

Future work

- Having recently began to consider the importance and difficulty of the movement harmony among modules for realizing different gaits on surfaces of various materials, we are focusing on a kinematics model of the caterpillar's locomotion capabilities. The dynamics of the robot will be calculated with the Lagrange equation for system design and control purposes.
- This prototype will be used as an intelligent demonstrator and test bed for the implementation of cognitive functions in robotic systems. It will have flexible mobility to get to every point on different surfaces in the working space and will be able to carry multiple sensors and wireless communication.




Related publications

- H. Zhang. (2007), "***A Bio-inspired Climbing Caterpillar***", Patent (200710056722.9).
- J. González-Gómez, H. Zhang, et.al. "***Locomotion Capabilities of a Modular Robot with Eight Pitch-Yaw-Connecting Modules***", The 9th International Conference on Climbing and Walking Robots and their Supporting Technologies for Mobile Machines, CLAWAR2006, Brussels, Belgium, September 12-14, 2006.
- T. Zhu, R. Liu, X.D. Wang, K. Wang, "***Principle and Application of Vibrating Suction Method***", Proceedings of the 2006 IEEE International Conference on Robotics and Biomimetics, December 17 - 20, 2006, Kunming, China, pp.491-495.
- H. Zhang, J. Gonzalez-Gomez, S. Chen, W. Wang, R. Liu, D. Li, J. Zhang, "***A Novel Modular Climbing Caterpillar Using Low-frequency Vibrating Passive Suckers***", Proceeding of 2007 IEEE/ASME International Conference on Advanced Intelligent Mechatronlics, ETH Zurich , Switzerland, 4 - 7 Sept.2007.

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- Introduction to three kinds of climbing prototypes
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  - Gecko climbing robot
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Mobile Robotics

A Miniature Wall-climbing Robot

Lecturer

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TAMS, Department of Informatics
University of Hamburg, Germany

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Outline of this part

- Introduction
- Overview of prototypes design
  - First version
  - Second version
- Further implementation

Outline of this part

- Introduction
- Overview of prototypes design
  - First version
  - Second version
- Further implementation

Introduction

- A miniature climbing robotic platform in urban environments needs to be small and be mobile enough for traveling on the exterior and interior surfaces of buildings.
- The major challenge in designing this climbing robotic system is the ability to overcome the different kinds of obstacles in the work space.
- The robot should be capable of carrying multiple sensors and wireless communication devices in order to carry out the tasks independently.

Requirements for our project

- Climbing ability on walls of different materials such as glass, metal, plastic, tiles;
- Velocity: about 50-100mm/s;
- Traveling between surfaces with a 0-90 degrees angle;
- The ability to cross obstacles (height $\times$ width = 50mm $\times$ 50mm)
- Gross weight: 10 kg;
- Carrying tools and sensors;
- No connection with the remote GUI.

Outline of this part

- Introduction
- Overview of prototypes design
  - First version
  - Second version
- Further implementation

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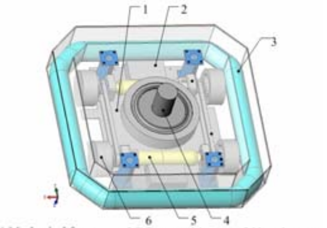
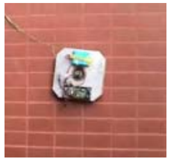
First version of our design

- We proposed a lightweight smart wall-climbing robot in 2005, which was developed as a flexible mobile platform carrying a CCD camera and other sensors. Firstly we designed a semi-autonomous climbing prototype with wheels and negative pressure, as shown in figure.



1.Mechanical frame 2.DC motor drivers 3.Negative cup
4. DC motor for negative cup 5.DC motors 6.Wheel

Research on a smart mechanism

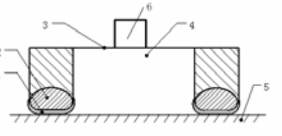


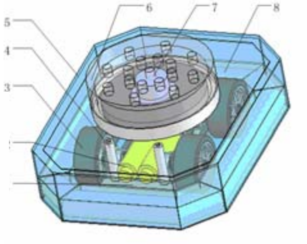
Second version of climbing Gecko

- The second version
  - We improved the first version on several aspects in 2005-2006.
  - Reduced weight and size
  - Features sensors and a wireless interface
  - Is controlled in two different ways

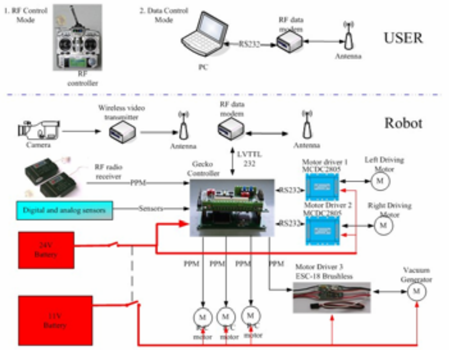
Mechanical part

- The moving body is contained in a negative pressure cup. The rubber gasbag is charged for keeping vacuum. The two parts of the robot are connected by four pillars. The motor to generate negative pressure is installed on the top of the cup.





Control system



Outline of this part

- Introduction
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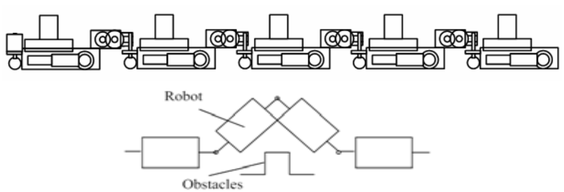
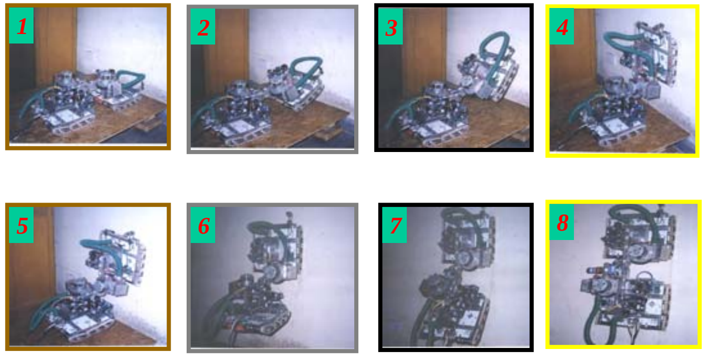
Further implementation

Miniaturization；modularization；flexibility; multi-function

Any two robotic modules can connect using the connection part and the gears. For a crossing function and for moving between two surfaces, a micro-dc motor is used to release the locking pin located at the connecting part between two modules. When the connecting joint is in a free state as shown in the figure. A module can rotate at a 0-90 degrees angle actuated by another DC motor and a set of gears to reconstruct the body.

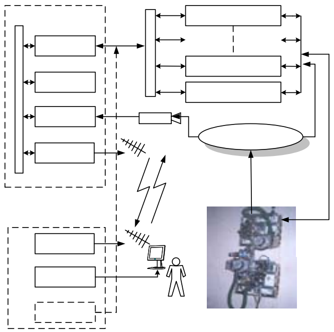


Traveling between two surfaces



Control system

- Requirements:
  - functionality;
  - safety;
  - extensibility;
  - easy handling;
  - and low cost.
- A distributed control system based on CAN bus;
- 7 parts, 6 CAN bus control nodes and a remote controller.



Outline of today's lecture

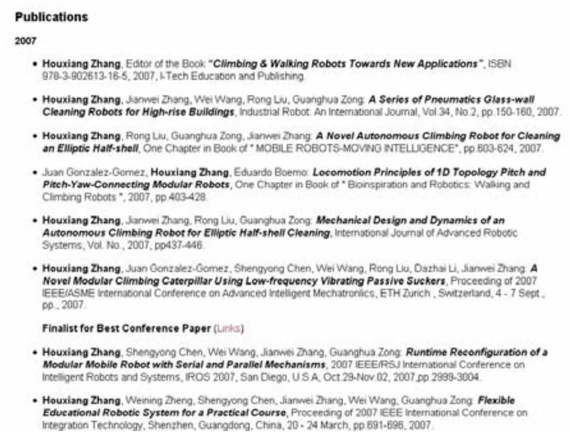
CAN Card

CAN Bus

Distributed Controller

Conclusions

- A review on climbing robots
- Classification of climbing robots
- Sky cleaner family introduction
- A modular climbing caterpillar
- Gecko climbing robot



Publications

2007

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- **Houxiang Zhang**, Rong Liu, Guanghua Zong, Jianwei Zhang: ***A Novel Autonomous Climbing Robot for Cleaning an Elliptic Half-shell***, One Chapter in Book of " MOBILE ROBOTS-MOVING INTELLIGENCE", pp.603-624, 2007.
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  Finalist for Best Conference Paper (Links)
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Thanks for your attention!

Any questions?