Proseminar Roboter und Aktivmedien
Climbing robots achievements and challenging

Lecturer
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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

Research on climbing mechanisms

- Multiple-legged kinematics

Research on climbing mechanisms

- Gecko
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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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

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.
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;
  - Building maintenance;
  - Inspired research

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

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.

Climbing robots classification

- According to the attachment principles:
  - Electromagnetic force
  - Molecular force
  - Mechanical force
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- According to kinematics:
  - Legged robot;
  - Sliding frame robot;
  - Wheeled robot and chain-tracks

- According to applications:
  - Industrial inspection;
  - Urban search and rescue;
  - Building maintenance;
  - Inspired research

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 (cm²): 52.5
- Lightweight: <500g
- Vacuum suction
- Move very slowly
- Without enough sensors on board

ROSTAM-III

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

Legged climbing robot

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

Alicia robot (Catania, 2000)

- Dimension (cm²): 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.

Climbing robots classification

- According to the attachment principles
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- According to kinematics
  - Sliding frame robot;
  - Legged robot;
  - Wheeled robot and chain-tracks
- According to applications
  - Industrial inspection;
  - Urban search and rescue;
  - Building maintenance;
  - Inspired research
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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- Background of cleaning robots
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  - Sky Cleaner 1
  - Sky Cleaner 2
  - Sky Cleaner 3
- Nonlinear control algorithms
- Conclusions

Background of cleaning robots

Outer glass wall cleaning
Technical Aspects of Multimodal Systems
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37

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38

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39

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40

Outer glass wall cleaning

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.

Study on Operation Targets

- 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));

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

Why design pneumatic robots
- Advantage
  - Lightweight
  - Passive compliance, safer than driven by motors
- Disadvantage
  - Nonlinearities and low stiffness
Advantages of the pneumatic system

<table>
<thead>
<tr>
<th>Item</th>
<th>Driven linear guidance unit</th>
<th>Pneumatic</th>
<th>Electrical</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>NEFF</td>
<td>NAGREN</td>
</tr>
<tr>
<td>Model</td>
<td></td>
<td>NGE-6000</td>
<td>NAG-6000</td>
</tr>
<tr>
<td>Force (Fdrive)</td>
<td>75</td>
<td>75</td>
<td>67</td>
</tr>
<tr>
<td>MX (NM)</td>
<td>39</td>
<td>19.6</td>
<td>16</td>
</tr>
<tr>
<td>MY (NM)</td>
<td>110</td>
<td>58.8</td>
<td>87</td>
</tr>
<tr>
<td>MZ (NM)</td>
<td>110</td>
<td>19.6</td>
<td>50</td>
</tr>
<tr>
<td>Weight for linear unit (kg)</td>
<td>4.9</td>
<td>8.9</td>
<td>6.6</td>
</tr>
<tr>
<td>Weight for actuator (kg)</td>
<td>10.0</td>
<td>15.0</td>
<td>10.0</td>
</tr>
<tr>
<td>Connectors (kg)</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Total weight (kg)</td>
<td>11.7</td>
<td>7.2</td>
<td>8.2</td>
</tr>
</tbody>
</table>

Definition: Power-to-weight ratio = \( \frac{F_{\text{drive}}}{G_{\text{drive}}} \)

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

Outline of this part

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  - Sky Cleaner 2
  - Sky Cleaner 3
- Nonlinear control algorithms
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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.

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Sky cleaner 2

- 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 m²/hour.

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 m²/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

1. the supporting vehicle
2. hose
3. sky cleaner
4. cables
5. kickstand
6. the top of the building
7. the following unit
8. glass wall
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.

Software hierarchy
Some photos about cleaning in Shanghai

Conclusions

<table>
<thead>
<tr>
<th>Type</th>
<th>Sky Cleaner 1</th>
<th>Sky Cleaner 2</th>
<th>Sky Cleaner 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target character</td>
<td>Glass wall 0° - 45°</td>
<td>Glass wall 0° - 90°</td>
<td>Glass wall 0° - 90° (with &lt; 2° angle)</td>
</tr>
<tr>
<td>Efficiency (m²/8 hours)</td>
<td>37.5</td>
<td>75</td>
<td>100-125</td>
</tr>
<tr>
<td>Cross obstacles (mm²):</td>
<td>Window frame: 30x60; Seal: 3x20</td>
<td>Window frame: 30x60; Seal: 3x20</td>
<td>Window frame: 30x60; Seal: 3x20</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>25</td>
<td>25</td>
<td>45</td>
</tr>
<tr>
<td>Body Mass (cm³):</td>
<td>935 x 900 x 320</td>
<td>1220 x 1340 x 370</td>
<td>1136 x 736 x 377</td>
</tr>
<tr>
<td>Supporting unit</td>
<td>Supporting vehicle</td>
<td>Supporting vehicle and following unit</td>
<td>Supporting vehicle and following unit</td>
</tr>
<tr>
<td>Operations</td>
<td>1</td>
<td>1-2</td>
<td>1-2</td>
</tr>
<tr>
<td>Water supply (L/hour)</td>
<td>50 (reused)</td>
<td>50 (reused)</td>
<td>50 (reused)</td>
</tr>
</tbody>
</table>

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Schemes of the X and Y cylinders

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Control model of the X cylinder

\[
\begin{align*}
F_1 & = F_2 \\
S & \rightarrow O \quad \text{Object of a perfect position servo control algorithm:} \\
|SO| & = 0 \\
\text{Then } & a = 0
\end{align*}
\]

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, \( T_o \) is on-time. Because there exist electrical and mechanical delays on the valve, the pressure output of the valve is generally like the curve in the right figure. Where \( T_o \) is the delay time of on, \( T \) is the delay time of off. Both the delay times are determined by the response time of the solenoid valve.
- 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.

\[
\tau = \frac{T_o}{T} \times 100\%
\]

Characteristics of pneumatic system

- Characteristics of the pneumatic cylinders

Different pneumatic control algorithms

- Fuzzy PID for Sky Cleaner 1
Different pneumatic control algorithms

- Fuzzy PID for Sky Cleaner 1

\[ \tau = \begin{cases} 
100 & k_f(x_f - x) \geq 100 \\
0 & 0 \leq k_f(x_f - x) \leq 100 \\
0 & k_f(x_f - x) \leq 0 
\end{cases} \]

Where \( k_f \) is proportional coefficient, \( x_f \) is the desired position, \( x \) is the current position. When the cylinder arrives at the desired position, the brake cylinders will mechanically stop it.

- Proportional control with mechanical brakes for Sky Cleaner 2

<table>
<thead>
<tr>
<th>No.</th>
<th>Desired position (mm)</th>
<th>Errors (mm)</th>
<th>( e_{\text{max}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50.0</td>
<td>1.86</td>
<td>2.25</td>
</tr>
<tr>
<td>2</td>
<td>50.0</td>
<td>1.48</td>
<td>1.94</td>
</tr>
<tr>
<td>3</td>
<td>50.0</td>
<td>2.23</td>
<td>2.33</td>
</tr>
<tr>
<td>4</td>
<td>50.0</td>
<td>2.37</td>
<td>2.72</td>
</tr>
<tr>
<td>5</td>
<td>50.0</td>
<td>1.98</td>
<td>0.96</td>
</tr>
</tbody>
</table>

- Fuzzy PID for Sky Cleaner 1

Different pneumatic control algorithms

- Proportional control with mechanical brakes for Sky Cleaner 2
Different pneumatic control algorithms

- for Sky Cleaner 2

<table>
<thead>
<tr>
<th>No.</th>
<th>Desired position (mm)</th>
<th>errors (mm)</th>
<th>$\Delta \theta_{\text{max}}$</th>
<th>Desired position (mm)</th>
<th>errors (mm)</th>
<th>$\Delta \theta_{\text{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30.0</td>
<td>1.09</td>
<td>0.16</td>
<td>30.0</td>
<td>1.40</td>
<td>0.40</td>
</tr>
<tr>
<td>2</td>
<td>30.0</td>
<td>1.129</td>
<td>0.76</td>
<td>30.0</td>
<td>0.82</td>
<td>0.58</td>
</tr>
<tr>
<td>3</td>
<td>30.0</td>
<td>1.36</td>
<td>0.55</td>
<td>30.0</td>
<td>1.28</td>
<td>0.48</td>
</tr>
<tr>
<td>4</td>
<td>30.0</td>
<td>0.05</td>
<td>0.00</td>
<td>30.0</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Conclusions and recommendations

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

$$y - v - c_n \cdot \text{sgn}(v) \leq e_n \leq y - v - c_n \cdot \text{sgn}(v)$$

- 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 $n$. 

$$y - v - c_n \cdot \text{sgn}(v)$$
Parameter C

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

\[
y = c - ce^{-\frac{\pi}{c}} \text{sgn}(e)
\]

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

Conclusions and recommendations

- Here \( c \) is set to five for the realization.

\[
y = c - ce^{-\frac{\pi}{c}} \text{sgn}(e)
\]

The pressure should be as high as possible.
Different pneumatic control algorithms

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

<table>
<thead>
<tr>
<th>No.</th>
<th>Condition</th>
<th>Status Position</th>
<th>Actual Position</th>
<th>Assignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>z=6, SkMPa, C=5, e=10mm, T=35mm, Emax=10mm</td>
<td>50.0</td>
<td>50.0</td>
<td>( \sigma = \sum N_i \times (a + 9.91)</td>
</tr>
<tr>
<td>2</td>
<td>z=6, SkMPa, C=5, e=10mm, T=35mm, Emax=10mm</td>
<td>50.0</td>
<td>50.0</td>
<td>( \sigma = \sum N_i \times (a + 9.91)</td>
</tr>
</tbody>
</table>

The shortcomings:
1. Non-zero acceleration value when \( \varepsilon < \) limit value
2. The effect of friction is ignored

PWM-based cylinder driving system

Original Cylinder Driving System

Phase plane portrait of switch evaluation function

Basic variable bang-bang control algorithm

- Switch evaluation function
- \( y = \text{sign}(e) \)
- \( U_i = U_{i-1} \times \text{sgn}(y) \)
- \( i=1,2 \)
- \( e = e_1 + e_2 \)
- \( y_{01} \), \( y_{10} \): Switch evaluation function
- \( e_1, e_2 \): Position error
- \( C \): Undetermined plus constant
- \( \text{sgn}() \): Sign function
- \( U_i \): Control signal
- \( \varepsilon \): Combined error index

The shortcomings:
1. Non-zero acceleration value when \( \varepsilon < \) limit value
2. The effect of friction is ignored

F&A compensating control algorithm

- \( F_1 = (m|a| + F_{max}) / (1-p) \)
- \( F_2 = p \times F_1 \)
- \( F_1 = (m|a| - F_{max}) / (1-p) \)
- \( F_2 = p \times F_1 \)
- \( F_1 = (m|a| + F_{max}) / (1+p) \)
- \( F_2 = p \times F_1 \)
- \( F_1 = (m|a| - F_{max}) / (1+p) \)
- \( F_2 = p \times F_1 \)
- \( F_1 = (m|a| + F_{max}) / (1-p) \)
- \( F_2 = p \times F_1 \)

- \( m \): Mass of piston and load
- \( \varepsilon \): Combined error index
- \( \varepsilon_{\text{max}} \): Limit of error
- \( p < 1 \): Back pressure coefficient to enhance the cylinder rigidity
- \( F_{\text{max}} \): Pushing force under air pressure
Discrimination of $F_R$

$$F_R = F_F + bv$$

$F_F$: Gross friction on piston
$F_S$: Breakdown friction of cylinder
$b$: Damp coefficient
$v$: Velocity of piston
$\text{sgn}(v)$: Sign function
$F_D$: Dynamic friction

Discrimination of FR

$$FR = FF + bv$$

$FF$: Gross friction on piston
$FS$: Breakdown friction of cylinder
$b$: Damp coefficient
$v$: Velocity of piston
$\text{sgn}(v)$: Sign function
$F_D$: Dynamic friction

Determination of expectative acceleration $a$

$$a = \begin{cases} \frac{d_e}{dt} & \text{Step function of } a \\ \frac{E_3}{a} & \text{Arc-tangent function of } a \\ \frac{E_2}{a} & \text{Linear function of } a \\ a_k & \text{Step function of } a \end{cases}$$

$$E_1 = E_2 = \frac{|e_s|}{3}$$

Results of position servo test for X cylinder

<table>
<thead>
<tr>
<th>Testing condition</th>
<th>Air source pressure $P_o = 6MPa$, Distance: $e_s = 148mm$, $C = 3$, $T_{max} = 0.5$, $F_L = 300N$, $m = 32Kg$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step function</td>
<td>Averages value: 144.80mm, Average steady time: 1.06s, Variance analysis: 0.17mm, Repeating precision: 0.048mm, Max overshoot: 2.2mm</td>
</tr>
<tr>
<td>Linear function</td>
<td>Averages value: 142.29mm, Average steady time: 1.12s, Variance analysis: 0.17mm, Repeating precision: 0.048mm, Max overshoot: 2.2mm</td>
</tr>
<tr>
<td>Arc-tangent function</td>
<td>Averages value: 148.14mm, Average steady time: 1.64s, Variance analysis: 0.32mm, Repeating precision: 0.096mm, Max overshoot: 1.4mm</td>
</tr>
</tbody>
</table>
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.

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- Review of climbing robots
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- Introduction to three kinds of climbing prototypes
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  - A modular climbing caterpillar
  - Gecko climbing robot
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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
Outline of this part

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

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.*
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.

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.

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.
Outline of this part

- Our idea
- Overview of prototype design
- Low-frequency vibrating passive suckers
- 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

Outline of this part

- Our idea
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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:

\[ y_i = A_i \sin\left(\frac{2\pi}{T} t + \phi_i\right) + O_i \]

- Where \( y_i \) is the rotation angle of the corresponding module; \( A_i \) is the amplitude; \( T \) is the control period; \( t \) is time; \( \phi_i \) 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.

- \( \Delta \phi \) is the phase difference between two adjacent vertical modules.
- \( \Delta \phi \) is the phase difference between two adjacent horizontal modules.
- \( \Delta \phi \) is the phase difference between two adjacent horizontal and vertical modules.

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Gate types Parameters for sinusoidal generators

<table>
<thead>
<tr>
<th>Gate types</th>
<th>Parameters for sinusoidal generators</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear</td>
<td>( A_{Vi} = 0; A_{Hi} = 0; O_{Hi} = 0; O_{Vi} = 0 )</td>
</tr>
<tr>
<td>Turning</td>
<td>( \Delta \phi_V = 100-120; O_{Hi} = 0 )</td>
</tr>
<tr>
<td>Rolling</td>
<td>( A_{Hi} = 0; O_{Hi} = 0 )</td>
</tr>
<tr>
<td>Lateral</td>
<td>( \Delta \phi_V = 100-120; \Delta \phi_H = 0 )</td>
</tr>
<tr>
<td>Rotation</td>
<td>( \Delta \phi_V = 120; \Delta \phi_H = 0; \Delta \phi_{HV} = 50 )</td>
</tr>
</tbody>
</table>
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.

Implementation (cont’)

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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

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

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 × width = 50mm × 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
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.

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

Research on a smart mechanism

- 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.
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.

Control system

Outline of this part
- Introduction
- Overview of prototypes design
  - First version
  - Second version
- Further implementation
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.

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Conclusions

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

- Special thanks to the “863” plan in China for supporting “Sky cleaner” projects.

- Also, thanks to the ARMS Group at Beijing University of Aeronautics and Astronautics (BUAA) for the technical cooperating on climbing and cleaning robotic projects.

- The modular robot project was developed in cooperation with my colleague Juan Gonzalez-Gomez from the School of Engineering, Universidad Autonoma de Madrid in Spain.

Thanks for your attention!

Any questions?