Dynamic Obstacle-Crossing of a Wheeled Rover with Double-Wishbone Suspension

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14th International Conference on Climbing and Walking Robots
6 - 8 September 2011
2011
All-terrain robots

- Most of existing commercial all-terrain mobile robots are **slow** (< 3-5m/s)
  - Low speed allows **special modes of locomotion** such as obstacle climbing modes for de-mining or industrial inspection
  - Low speed is also suitable for home use / gaming

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**PackBot 510 (iRobot)**
- 89cm, 11kg, 2.6m/s
- [www.irobot.com](http://www.irobot.com)

**Arthron R (M-Tecks EAC)**
- 50cm, 10kg, 3m/s
- [www.m-teckseac.com](http://www.m-teckseac.com)

**robuCAR TT (Robosoft)**
- 2m, 350kg, 5m/s
- [www.robosoft.com](http://www.robosoft.com)

**Speekee (Meccano)**
- 30cm, 3.5kg, 0.3m/s
- [www.spykeeworld.com](http://www.spykeeworld.com)
Fast all-terrain robots

- Many outside applications could benefit from **high speed** (more than 10m/s)
  - **Inspection** of vast areas such as airports or industrial facilities
  - Fast robots → less robots that are more dissuasive
  - Terrestrial drones: safer + larger autonomy than aerial drones
  - **Agriculture**: weeding, seeding
  - Casualty detection in case of **disaster**

Airport facilities
(Toulouse-Blagnac airport and Airbus facilities)

Inspection task after Fukushima disaster, 2011 (Photo: BBC)
Fast obstacle-crossing

- How to manage obstacle-crossing at **high speed**?
- Few work relate to the **frontal crash** on an obstacle
  - Robots thrown above obstacles
  - Crash study based on non-linear FEM
  - Experiments on a pick-up (2 tons)

Dynamic Obstacle Crossing

- All-terrain
  - Market
  - FAST
  - Goals

Experiment

Model

Conclusion

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IFMA, Clermont-Ferrand

14th International Conference on Climbing and Walking Robots, 6-8 September 2011, Paris
The ANR FAST Project

**FAST** project (**F**ast **A**utonomous Rover **S**ys**T**em)

- Funded by the French **N**ational **A**gency for **R**esearch (ANR) 2007-2011
- General goal: design an autonomous mobile robot capable to **safely move at 10m/s on all-terrain**
- Team:

- Scientific objective (among others): mechatronics design of a **dynamically auto-stable robot**
- Problem specifications:
  - Unstructured natural environment
  - Vehicle scale: from 0.3m to 2.5m
  - Speed > 10m/s
  - Obstacles

Typical addressed environment

Moors from Plateau des Millevaches
Experimenting

- First, an experimental approach of obstacle-crossing
  - Complex phenomena: non-linear fast crash of deformable mechanisms with friction and sliding
  - Experimenting allows to evaluate the most suitable laws to introduce in a simplified model, that will be presented in Part 3

- Choosing a mobile platform
  - A fast & robust vehicle
  - Small scale decreases the repair cost
  - Easy to tip-over

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>E-Maxx</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>5.16 kg</td>
</tr>
<tr>
<td>L x l x h</td>
<td>518 x 419 x 242 mm</td>
</tr>
<tr>
<td>Wheelbase</td>
<td>335 mm</td>
</tr>
<tr>
<td>Track width</td>
<td>330 mm</td>
</tr>
<tr>
<td>Centre of mass</td>
<td>Centred</td>
</tr>
<tr>
<td>Wheel diameter</td>
<td>150 mm</td>
</tr>
<tr>
<td>Transmission</td>
<td>4x4</td>
</tr>
<tr>
<td>Max speed</td>
<td>14 m/s</td>
</tr>
</tbody>
</table>
Experimental obstacle

- **Adjustable C⁰ obstacle**
  - Steel bar adjustable in height h
  - Includes force measurement devices (Kistler 9257B)

- All-terrain in All-terra in
- Experiment
  - Vehicle
  - Obstacle
  - Speed
  - Force
  - Results
- Model
- Conclusion

Dynamic Obstacle Crossing

- Vertical rail for obstacle height adjustment
- Steel bracket
- Adhesive
- Kistler 3 component force sensor
- Steel obstacle square section 25mm x 25mm
- Steel mass of 5kg

Closing and Walking Robots, 6-8 September 2011, Paris
Speed measurement

- Speed measured by vision
  - 30 Hz camera located on top of the impact zone
  - Tiled floor with periodic pattern of 300mm
  - Instantaneous speed comes from the 2 last images before impact
Dynamic Obstacle Crossing

- 3 DOF force-plate
  - Acquisition 1kHz

Results
- Impact force increases with obstacle height
- Peaks of 400N
- \( F_x \approx F_z \) for \( v=8\text{m/s} \) and \( h=65\text{mm} \)
- Need for a horizontal component of suspension

<table>
<thead>
<tr>
<th>Parameter</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions (mm)</td>
<td>170</td>
<td>140</td>
<td>60</td>
</tr>
<tr>
<td>Force range (kN)</td>
<td>-5</td>
<td>+5</td>
<td>-5</td>
</tr>
<tr>
<td>Stiffness (kN/µm)</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Natural frequency (Hz)</td>
<td>2300</td>
<td>2300</td>
<td>3500</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>7.3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Forces \( F_x \) and \( F_z \) for variable height \( h \) and speed \( v=8\text{m/s} \):
Design of experiment (DoE)

- Summary of 77 experiments (h:25→75mm, v:3→8m/s)
  - High obstacles → crash by tip-over (red dots)
  - A stability front (red line) separates experiment with / without tip-over
  - The front has a decreasing non-linear shape
  - Future suspension with 2 DOF will enhance stability zone (green line)

Videos
Simple analytical model

- Frontal crossing configuration → 2D model

  ✓ 3 rigid bodies:
  2 wheel and the chassis → 9 DOFs

  ✓ Wheel / chassis suspension forces → vertical and longitudinal linear spring-dampers

  ✓ Wheel / ground contact forces → a new formula is proposed

  ✓ Wheel / obstacle impact force → linear spring-damper in function of penetration

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Equations of motion

- Newton-Euler equations

- Chassis equations

\[
\begin{align*}
\dot{m}_c \ddot{X}_c &= F_{x1} + F_{x2} \\
\dot{m}_c \ddot{Y}_c &= F_{y1} + F_{y2} - m_c g \\
I_{cz} \ddot{\theta}_c &= M_1 + M_2 - C_1 - C_2
\end{align*}
\]

- Wheel equations

\[
\begin{align*}
\dot{m}_i \ddot{X}_i &= T_i + R_{xi} - F_{xi} \\
\dot{m}_i \ddot{Y}_i &= N_i + R_{yi} - F_{yi} - m_i g \\
I_{zi} \ddot{\theta}_i &= C_i + rT_i
\end{align*}
\]
Wheel-ground contact

- **Normal force**
  - Linear spring damper model

- **Tangential force**
  - Novel formula valid for:
    - dynamic and static cases ($C_i=0$)
    - with and without slipping ($g_r=0$)

- **Impact forces**
  - Unilateral linear spring-damper force in function of penetration ($e$)
  - Experimental analysis with high speed camera at 10kHz

\[
N_i = \begin{cases} 
  k(r - Y_i) - c\dot{Y}_i & (Y_i \leq r) \\
  0 & (Y_i > r)
\end{cases}
\]

\[
T_i = N_i \min \left( g_r \mu - (1 - g_r) \frac{C_i}{r N_i}, g_r \mu \right)
\]

with slipping

\[
g_r = \frac{-r\dot{r}_i - \dot{X}_i}{\max(|r\dot{r}_i|, |X_i|)}
\]
Simulation results and DoE

- Simulation of frontal obstacle-crossing
  - Solving of the analytical equations with Matlab

- Design of Experiments with 100 experiments (h: 7→75mm, v: 1→10m/s)

**Videos**
Conclusion

- **Experimental part**
  - 77 experiments with an electric vehicle at scale 1/10
  - Wheel r: 75mm, Obstacle h: 25→75mm, Speed v: 3→8m/s
  - It exists a **tip-over stability limit** $f(h,v)=c$ with $f$ a decreasing non-linear stability frontier
  - The vehicle can cross
  - low obstacles at high speed
  - high obstacles at low speed

- **Analytical model**
  - 2D model based on dynamics and contact equations
  - Design of Experiments with 100 experiments
  - Close agreement with the decreasing tip-over stability limit

- **Impact forces**
  - Measurement of impact forces
  - $F_x$ is as high as $F_z$ and should be damped also
Future work

- A suspension with 2 DOF
  - The authors have shown [HUDEM 2010] that a horizontal DOF in the suspensions could benefit to longitudinal stability
  - An innovative suspension with 2 DOF based on a parallel mechanism has been designed and is under patent process
  - Analysis with high speed camera

Analytical model

- Refining the impact model by adding a non-constant stiffness
- Analytical expression of the stability frontier
- Optimization of front/rear and horizontal/vertical stiffness and damping coefficients
- Control strategy for optimal obstacle crossing