ME 222: Kinematics of Machines and Mechanisms

[L7] MEMS and Compliant Mechanism

Overview

- Spring as a link
- Case Study: Compliant modular robot

Case Study

- Design and Analysis of compliant Wheeled Robot for Urban Search And Rescue

Outline

- Motivation
- Design and optimization
- Some modifications

Urban Search And Rescue Situations

9/11 earthquake

Casualties:
- 2660 Civilians
- 430 Emergency Workers

Japan tsunami

Casualties:
- 15884 Civilians

Damage:
- 45000 buildings destroyed
- 144000 damaged

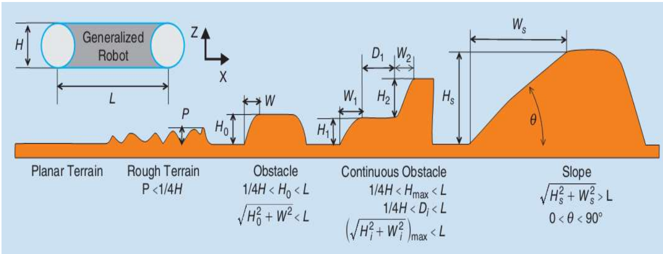
Uttarakhand

- Over 100000 were trapped.
- Nearly 18000 were airlifted
- 10000 army personnel deployed

Robots for Urban Search And Rescue Situations

- Searching for victims
- Searching for paths through the debris that would be quicker to excavate
- Structural inspection
- Detection of hazardous materials.

Complexity Of the Search and Rescue Efforts

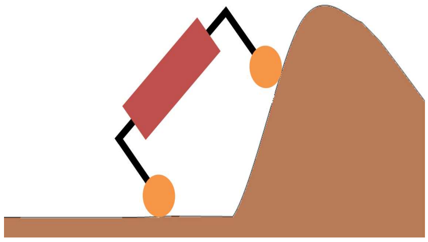


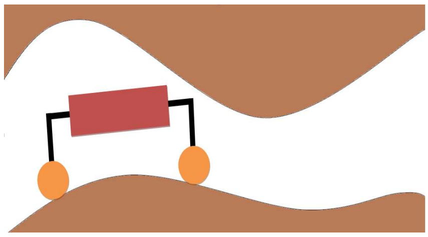
Parametrize Terrain

Robots in USAR

Desirable Attributes of a USAR Robot

- Durable
- Lightweight
- Economical
- Energy efficient
- Payload
- Highly traversable
- Versatile

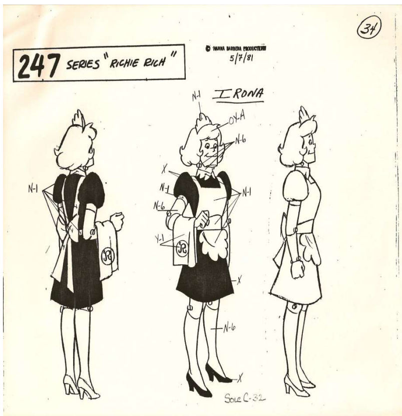


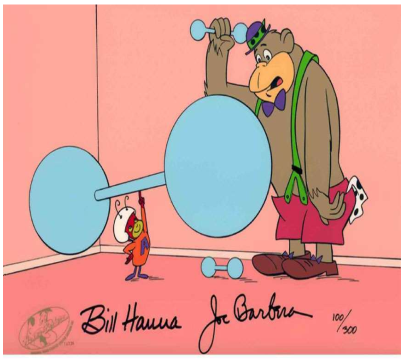


Various Kinds of Rough Terrain robots

Robots	Nature of Articulation	Max. traversable height is prop. to	Mode of Operation
Rocker-Bogie	Passive	Wheel Diameter	Open-Loop
Shrimp	Passive	Wheel Diameter	Open-Loop
CRAB	Passive	Wheel Diameter	Open-Loop
Hylos	Active	Link Length	Closed-Loop
PAW	Active	Link Length	Closed-Loop

The IDEAL robots

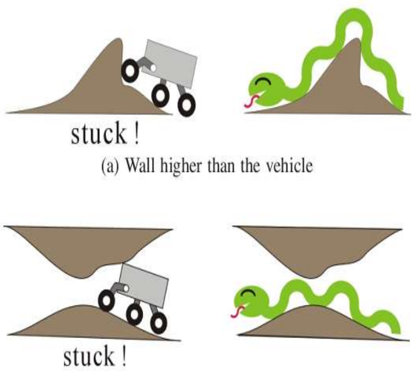




TW1102 "Magilla Gorilla and Atom Ant"
Eition Size: 300, Cel Size: 12F

Too good to be real!

Nature's Solution



(a) Wall higher than the vehicle

(b) Tight space

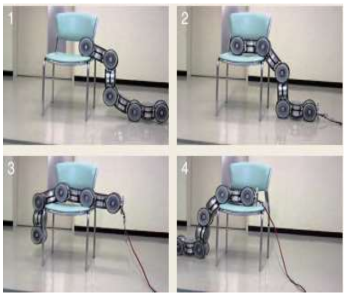
- The Snake!
  - Pros
  - highly redundant
  - slender
  - highly maneuverable
  - highly traversable
- Cons
  - speed!
  - climbing big-obstacles

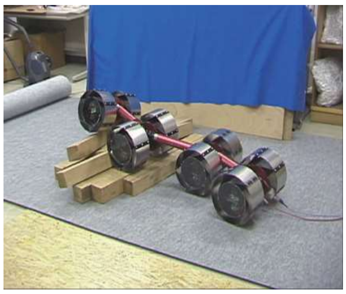
Snake-Like Robots

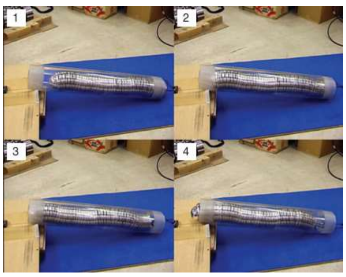
CLASSIFICATION OF SNAKE-LIKE ROBOTS

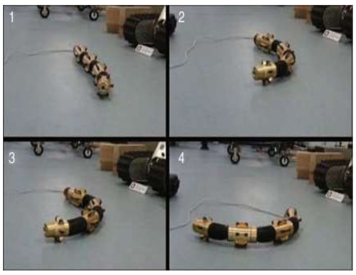
Existing Robots	Locomotion Mechanism	Trunk Actuation	Robot Category
ACM -R4	Wheel	Active	AW-AJ
Genbu	Wheel	Passive	AW-PJ
ACM-R3	Wheel	Active	PW-AJ
Shouryu III,IV,V	Crawler	Active	AC-AJ
Kohga	Crawler	Passive	AC-PJ

Snake-Like Robots



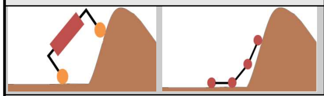
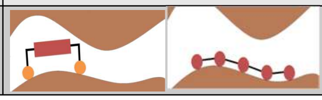
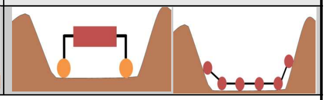






Compliant modular robot for Rough Terrain: Motivation

Urban Search And Rescue(USAR) operations

Bigger obstacles	Tight spaces	Ditches
		

Robots used in USAR

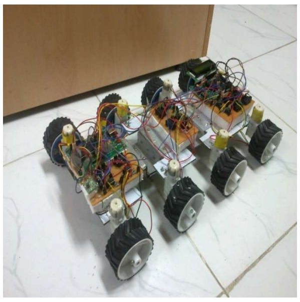
Snake-Like Robot – KOHGA

PackBot by iRobot

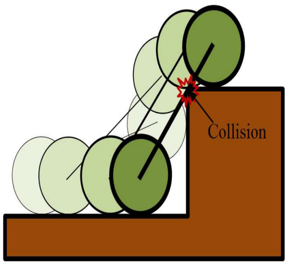
Pros of Wheels:

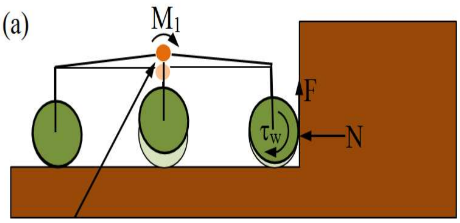
- Faster
- Easier to build and maintain

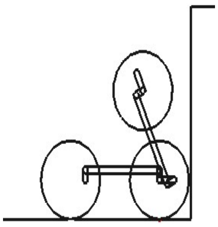
Proposed Design



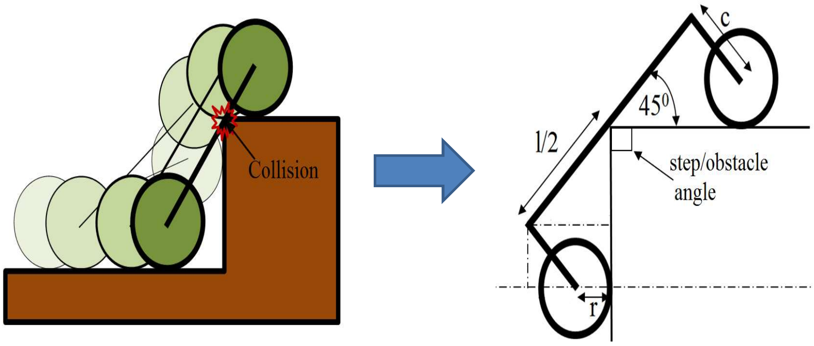
Some challenges



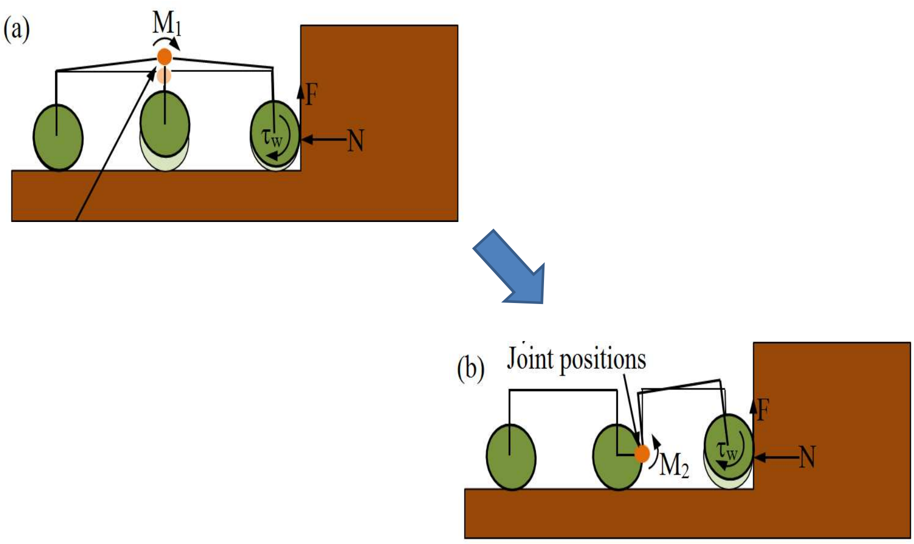




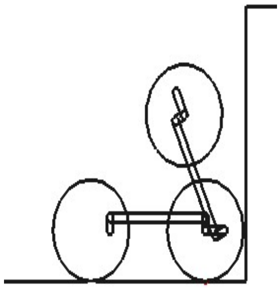
Solution to Problem 1



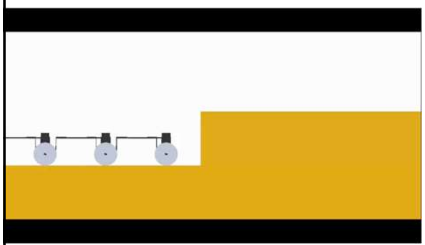
Solution to Problem 2

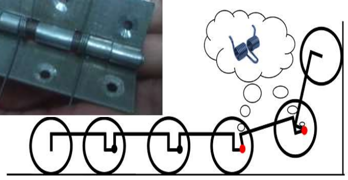


Problem 3 was rather challenging



Tip-over Problem





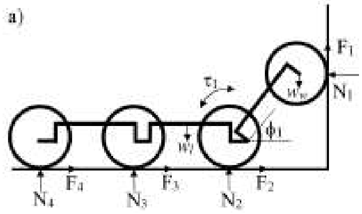
Compliant Joint Design

- Minimize link joint moments.

min $\sum_{j=1}^{p} (\tau_i^j - \tau_{i-i}^j)^2$ s.t. $\mathbf{F} \leq \mu \mathbf{N}$, $\mathbf{Q}(\mathbf{D}) = 0$

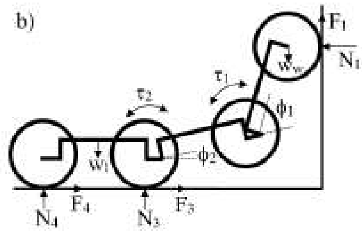
$$\boldsymbol{\tau} = [\tau_1 \ \tau_2]^T$$
$$\mathbf{F} = [F_1 \ F_2 \ F_3 \ F_4]^T$$
$$\mathbf{N} = [N_1 \ N_2 \ N_3 \ N_4]^T$$
$$\mathbf{D} = [\mathbf{F}^T \ \mathbf{N}^T \ \boldsymbol{\tau}^T]^T$$

Static Equilibrium



One module climbing

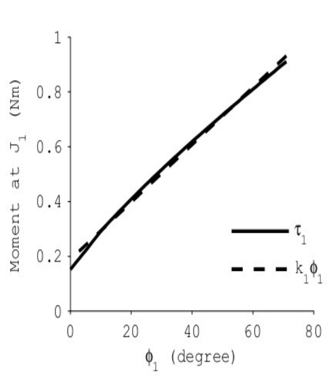
$$\sum F_x = 0 \quad N_1 - F_2 - F_3 - F_4 = 0 \tag{2}$$
$$\sum F_y = 0 \quad 3w_l + 8w_w - 2F_1 - 2N_2 - 2N_3 - 2N_4 = 0$$
$$\sum M_{J_1} = 0 \quad 2F_1 r + 2F_1 l cos\theta_1 + 2N_1 l sin\theta_1 - 2w_w l cos\theta_1 - w_l[(l/2)cos\theta_1 - c sin\theta_1] - \tau_1 = 0$$
$$\sum M_{J_2} = 0 \quad 2F_2 r + N_2 l - 2w_w l - w_l(l/2) - [(2w_w + w_l) - 2F_1](l + l_0) + \tau_1 - \tau_2 = 0$$
$$\sum M_{W_4} = 0 \quad 2F_3 r + 2F_4 r + 2N_3 l - 2w_w l - w_l(l/2) - [2(2w_w + w_l) - 2F_1 - 2N_2](l + l_0) + \tau_2 = 0$$

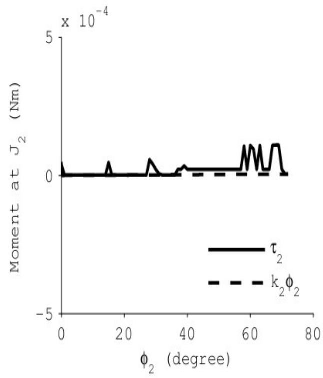


Two modules climbing

$$\sum F_x = 0 \quad N_1 - F_3 - F_4 = 0 \tag{3}$$
$$\sum F_y = 0 \quad 3w_l + 8w_w - 2F_1 - 2N_3 - 2N_4 = 0$$
$$\sum M_{J_1} = 0 \quad 2F_1 r + (2F_1 - 2w_w) l cos\theta_1 - w_l[(l/2)cos\theta_1 - c sin\theta_1] + 2N_1 l sin\theta_1 - \tau_1 = 0$$
$$\sum M_{J_2} = 0 \quad 2w_w(l + l_0)cos\theta_2 - w_l[(l/2)cos\theta_2 - c sin\theta_2] - [(2w_w + w_l) - 2F_1](l + l_0)cos\theta 2 + 2N_1(l + l_0)sin\theta_2 + \tau_1 - \tau_2 = 0$$
$$\sum M_{W_4} = 0 \quad 2F_3 r + 2F_4 r + 2N_3 l - 2w_w l - w_l(l/2) - [2(2w_w + w_l) - 2F_1 - 2N_2](l + l_0) + \tau_2 = 0$$

Joint stiffness

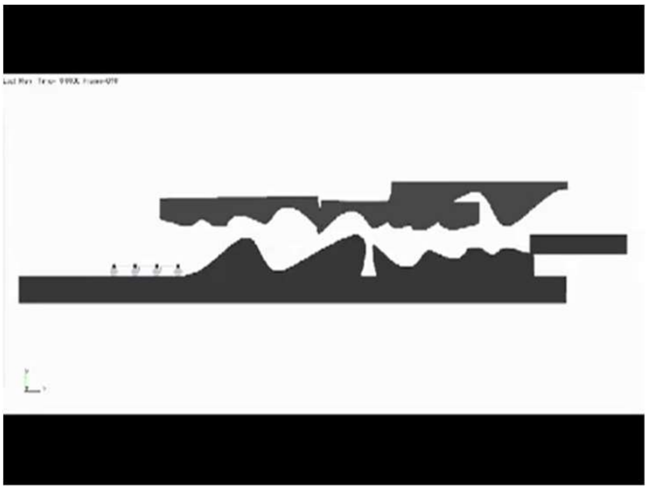




- Obtain joint stiffness by performing a least squares fit

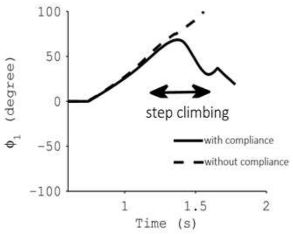
$$\underset{\mathbf{k}}{\text{minimize}} \quad \sum_{j=1}^{p} (\tau^j - \mathbf{k}\phi^j)^2$$

Experimental Implementation

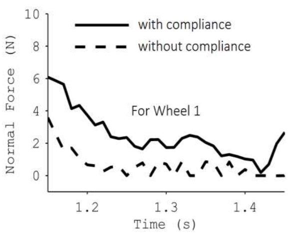


Avinash S, Srivastava A., Purohit A., **Shah S. V.** , and Krishna K. M., "A Compliant Robot for Climbing Big Step-like Obstacles," International Conference on Robotics and Automation (ICRA), Hong Kong, China, 2014 (ICRA is top conference in robotics).

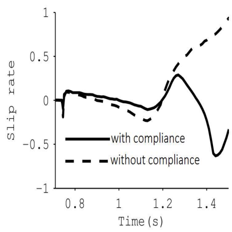
Some more results



Tip-over avoidance



Normal force redistribution



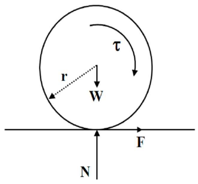
Marginal slip reduction

Wheel Slip Problem

- Wheel would start slipping when

$$F > \mu_s N$$

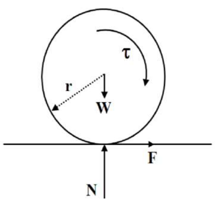
$F = \tau / r.$



- Disadvantages:
  - Energy loss
  - Odometry errors

- Control based on wheel torque optimization

Wheel-torque Based Traction Control

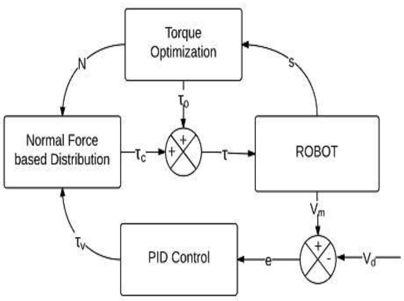


Wheel slip reduction:

min $\sum_{i=1}^{4} F_i / N_i$

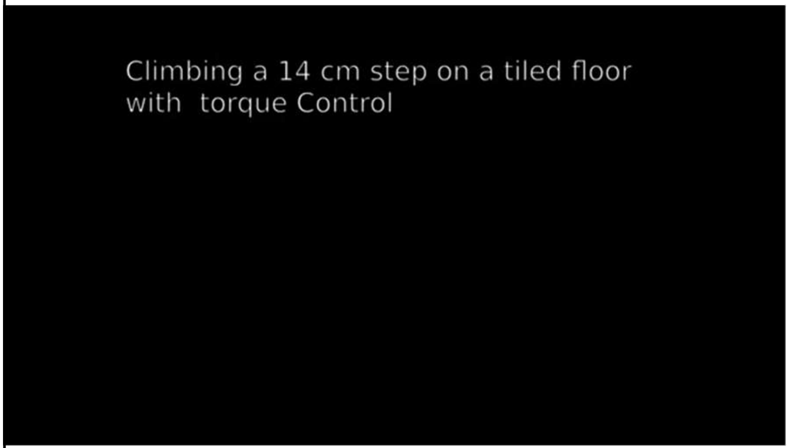
s.t.

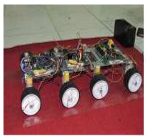
$$F_i \leq N_i \quad \forall\, i = 1 \ldots 4$$
$$0 \leq F_i \leq \tau_{wmax}/r \quad \forall\, i = 1 \ldots 4$$
$$phase\ 1: \quad N_i \geq N_{avg} \qquad i \in \{2,3,4\}$$
$$phase\ 2: \quad N_i \geq N_{avg} \qquad i \in \{3,4\}$$

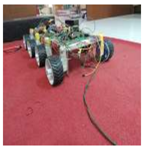


Avinash S, **Shah S. V.**, and Krishna K. M., "Wheel Torque Optimization and control for a Compliant Modular Robot," Robotica, 2014

Wheel-torque Based Traction Control



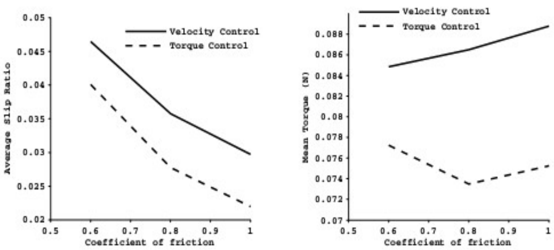


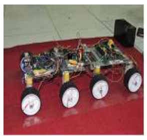


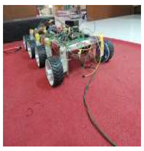
Avinash S, **Shah S. V.**, and Krishna K. M., "Wheel Torque Optimization and control for a Compliant Modular Robot," Robotica, 2014

Wheel-torque Based Traction Control

	Average Slip Ratio		Mean Torque (Nm)	
Floor Type	Velocity Control	Torque Control	Velocity Control	Torque Control
Tiled	0.188	0.0532	0.0867	0.0624
Carpeted	0.204	0.082	0.0796	0.0662
Taped	0.28	0.237	0.0799	0.0674
Wet	0.238	0.169	0.0724	0.0697



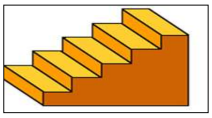




Avinash S, **Shah S. V.**, and Krishna K. M., "Wheel Torque Optimization for a Compliant Modular Robot,"1st International and 16th Nat. Conf. on Machines and Mechanisms (iNaCoMM), IIT Roorkee, India, 2013 (PDF).
Avinash S, **Shah S. V.** , and Krishna K. M., " An Optimal Torque Control for Wheel-Slip Minimization in a Compliant Wheeled Robot" Robotica, 2014.

Stair Climbing

- Key in (USAR) scenarios.
- Stair with angle 27 to 35°



Nomenclature followed in this video

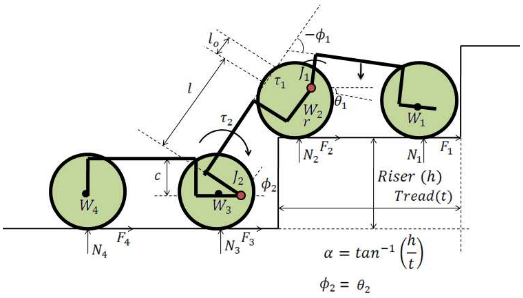
h = Riser length
t = Tread length
J1 = Joint-1
J2 = Joint-2

k(i)+/- = Stiffness of spring acting at Joint-i to counteract counter-clockwise (+)/clockwise (-) moments

Resist clockwise and counter clockwise moments

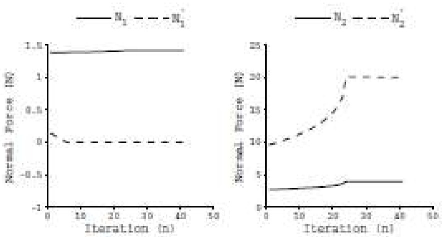
Turlapati T., Phani S. T., Shah M. , Avinash S., **Shah S. V.** , Krishna K. M., "Stair Climbing Using a Compliant Modular Robot," to IEEE/ International Conference on Intelligent Robots and Systems (IROS), 2015 (IROS h5 index: 45)

Stair Climbing



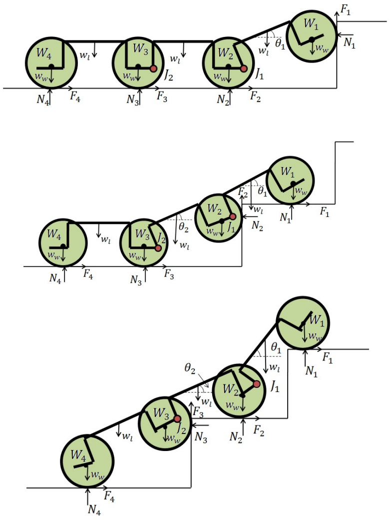
$$D_1(N_1' - N_1) = k_1^- \phi_1$$

$$D_2(N_2' - N_2) = \left[k_2^+ \phi_2 - k_1^- \phi_1 (1 - \frac{B}{D_1})\right]$$



Stair Climbing

- Key in (USAR) scenarios.
- Should resist both clockwise and counter clockwise moments
- Stair with angle 27 to 35°



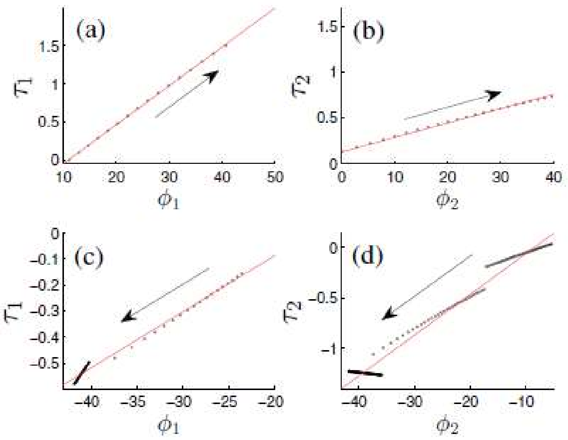
Maximize normal forces

max $N_{1,j}{}^2 + N_{2,j}{}^2 + N_{3,j}{}^2 + N_{4,j}{}^2$

s.t.
$$\mathbf{F_j} \leq min(\tau_{\mathbf{wmax}}/r, \mu \mathbf{N_j})$$
$$\mathbf{A_p x_p} = \mathbf{B_p}$$

Turlapati T., Phani S. T., Shah M. , Avinash S., **Shah S. V.** , Krishna K. M., "Stair Climbing Using a Compliant Modular Robot," to IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 2015 (IROS h5 index: 45)

Stair Climbing



$k_1^+ = 0.0506\ Nm/deg$
$k_2^+ = 0.0161\ Nm/deg$

$k_1^- = 0.0216\ Nm/deg,$
$k_2^- = 0.0267\ Nm/deg.$

Least squares fit: min $\sum_{j=1}^{p} (\tau^j - \mathbf{k}\phi^j)^2$

Turlapati T., Phani S. T., Shah M. , Avinash S., **Shah S. V.** , Krishna K. M., "Stair Climbing Using a Compliant Modular Robot," to IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 2015 (IROS h5 index: 45)

Stair Climbing

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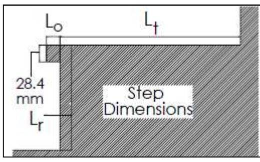
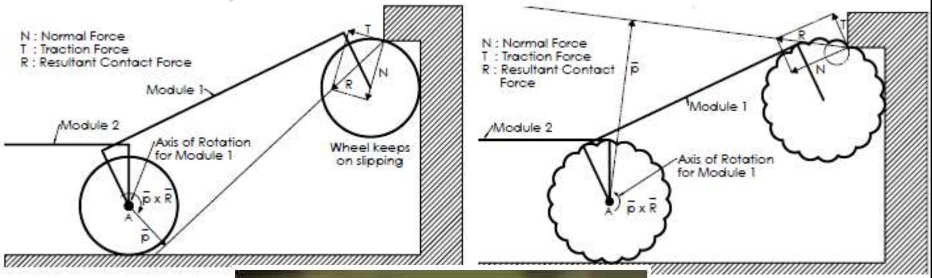
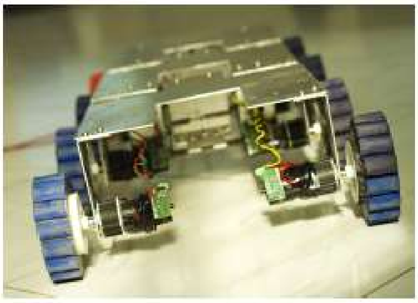
Overcoming Stairs with Overhung



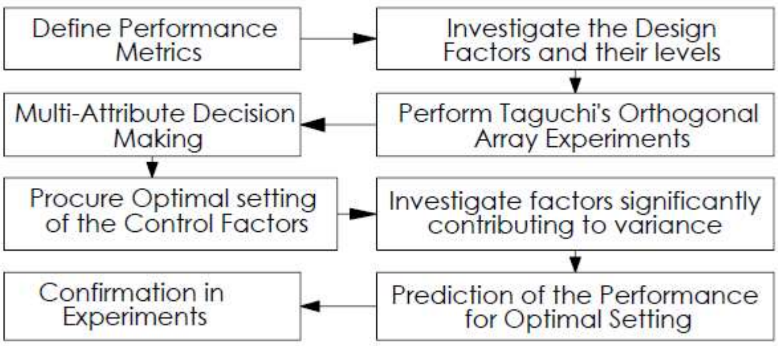
	Length of Overhang L_o(mm)	Length of Riser L_r (mm)	Length of Tread L_t (mm)
Step 1	23	177.8	304.8
Step 2	25	190.5	292.1
Step 3	27	203.2	279.4

Overcoming Stairs with Overhung





Procedure



Bhole A, Turlapati SH, Dixit J, **Shah S.V.**, Krishna KM. Design of a Robust Stair Climbing Compliant Modular Robot to Tackle Overhang on Stairs. arXiv preprint arXiv:1607.03077 (cs.RO), 2016

Overcoming Stairs with Overhung

Bhole A, Turlapati SH, Dixit J, **Shah S.V.**, Krishna KM. Design of a Robust Stair Climbing Compliant Modular Robot to Tackle Overhang on Stairs. arXiv preprint arXiv:1607.03077 (cs.RO), 2016

Detachable Modular Robot

Turlapati S. H., Srivastava A., Krishna K.M., Shah S.V. "Detachable Modular Robot capable of Cooperative Climbing and Multi Agent Exploration" IEEE International Conference on Robotics and Automation (ICRA), 2017 (PDF). (ICRA Google h5 index: 64)

Future Directions

- Variable Stiffness
- Steering
- 3D Motion
- Learning for autonomous rough terrain navigation

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- Hoping to see some of you carry the baton ☺

Thank you

Some practical consideration