Sun Tracking with Parallel Robots

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- Acknowledgements

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  Mohit Acharya

  Nils Bjorkman

  Sudipta Pramanik

  …. several other students
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Contents

Introduction

Solar Energy Harvesting

Flat photovoltaic panels
- ~18 – 20% efficiency
- Storage required
- Competitive with coal
- Kurnool, India – 1GW

Parabolic trough
- Rotation about one axis
- Incident energy focused on to a tube at focus
- ~20 % efficiency

Dish concentrator
- Parabolic dish
- Incident energy concentrated on to a Stirling engine
- Complete assembly tracks the sun – 2 axis motion
- Efficiency larger than PV/Parabolic trough >30%

Source: Google images/Wikipedia

Concentrated Solar Power Tower

Spain, USA, Australia, Middle East, North Africa, India, China etc.

- Concentrated solar power

  → large number (> 5000) of mirrors/heliostats

  → track sun and focus energy at a distant receiver (~500 m to ~1 km)

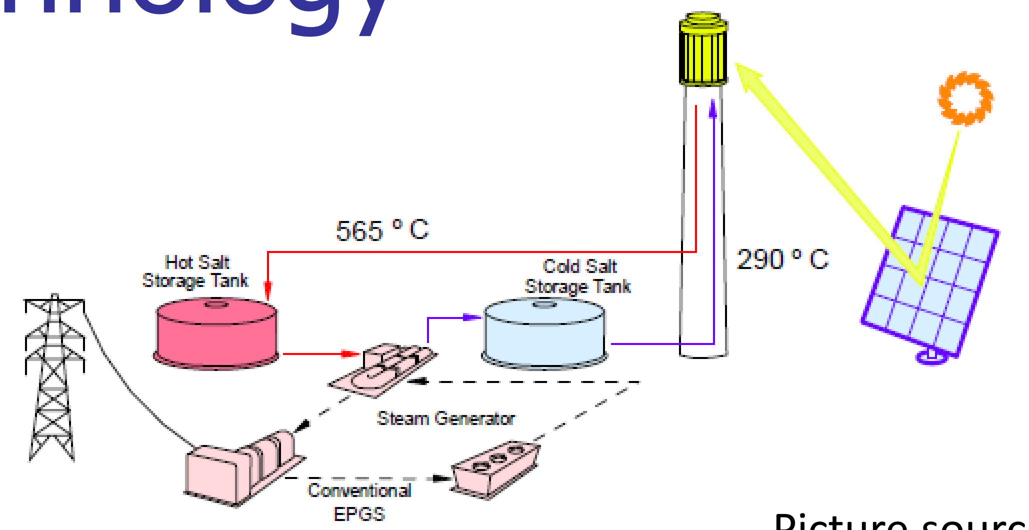
  -- high temperature at receiver → higher efficiency ~30%

  -- store solar energy as heat → no need for batteries

  → Very slow motion of the sun ~ 180 degrees in 12 hours; 2 axis motion

  → High accuracy requirement ~ 5 mrad pointing accuracy

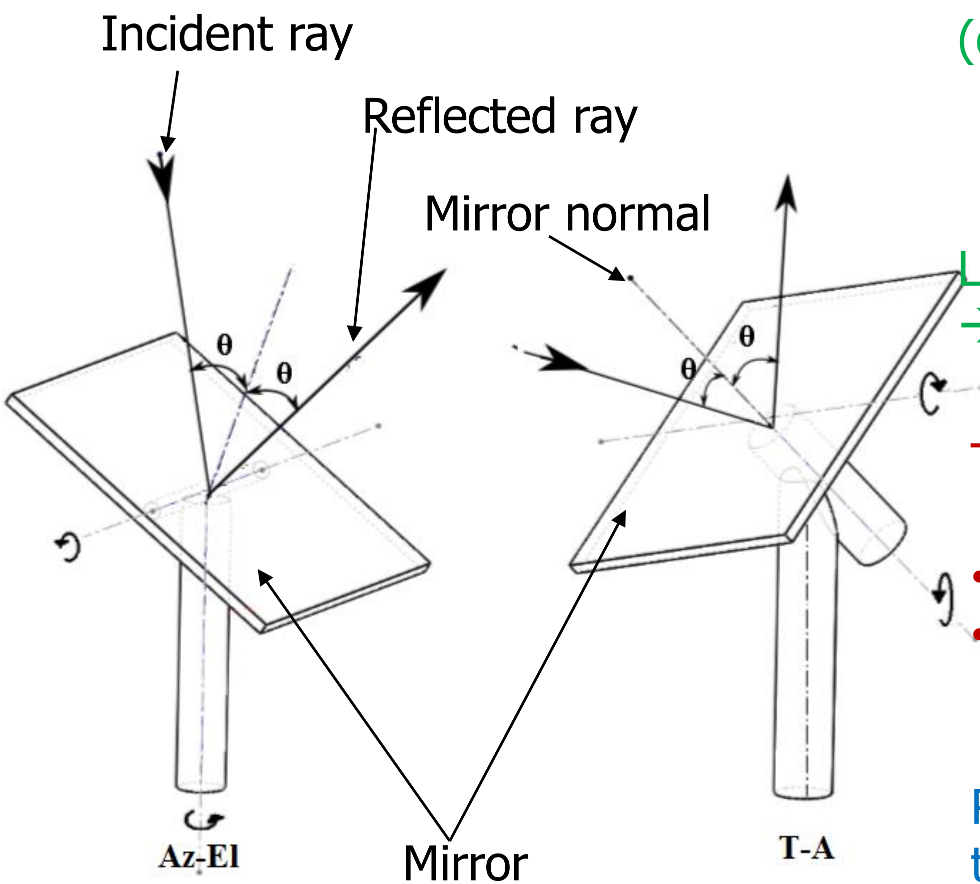
Solar Power Tower Technology



Picture source: Kolb (2007)

- Heliostat cost ~50 % of total investment cost (Kolb, 2009) – Target 80$ /m^2
- Solar Power Tower technology shows high potential for technology improvements (Lovegrove, 2012)

Existing Heliostats



Location of the sun in the sky known
(depends on latitude, longitude,
time of day and date)
→ Incident ray known

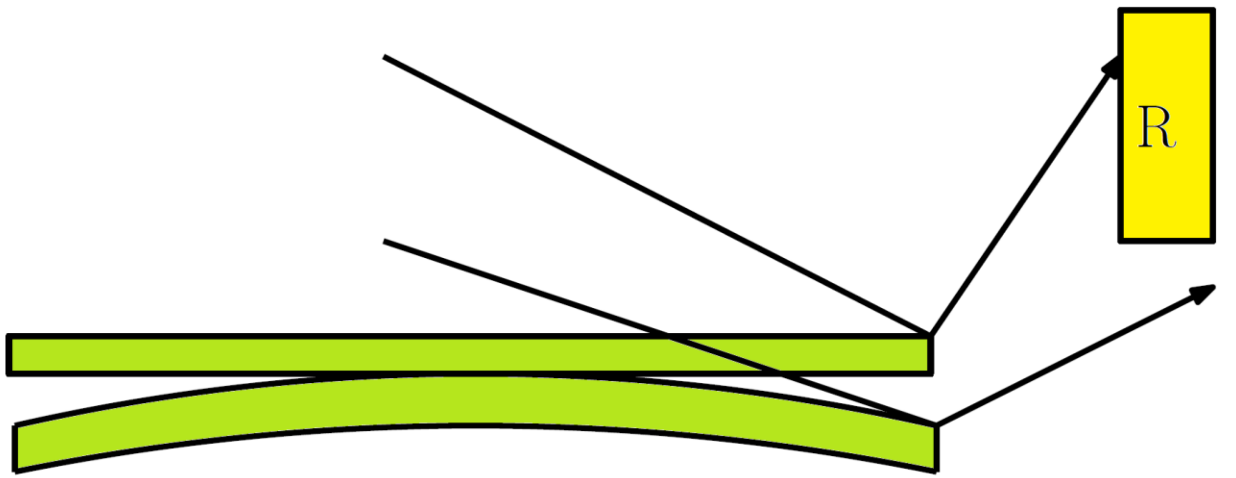
Location of receiver known
→ Reflected ray known

Two well known existing methods

- Azimuth-Elevation (Az-EL)
- Target-Aligned (T-A) or Spinning Elevation

Rotations about two perpendicular axes to align mirror normal appropriately

Limitations of Existing Heliostats



- Deflection may exceed slope error budget of 2-3 mrad due to wind loading and/or self-weight
  → Operational wind loading up to 10 m/sec, Survival wind loading 22 m/s

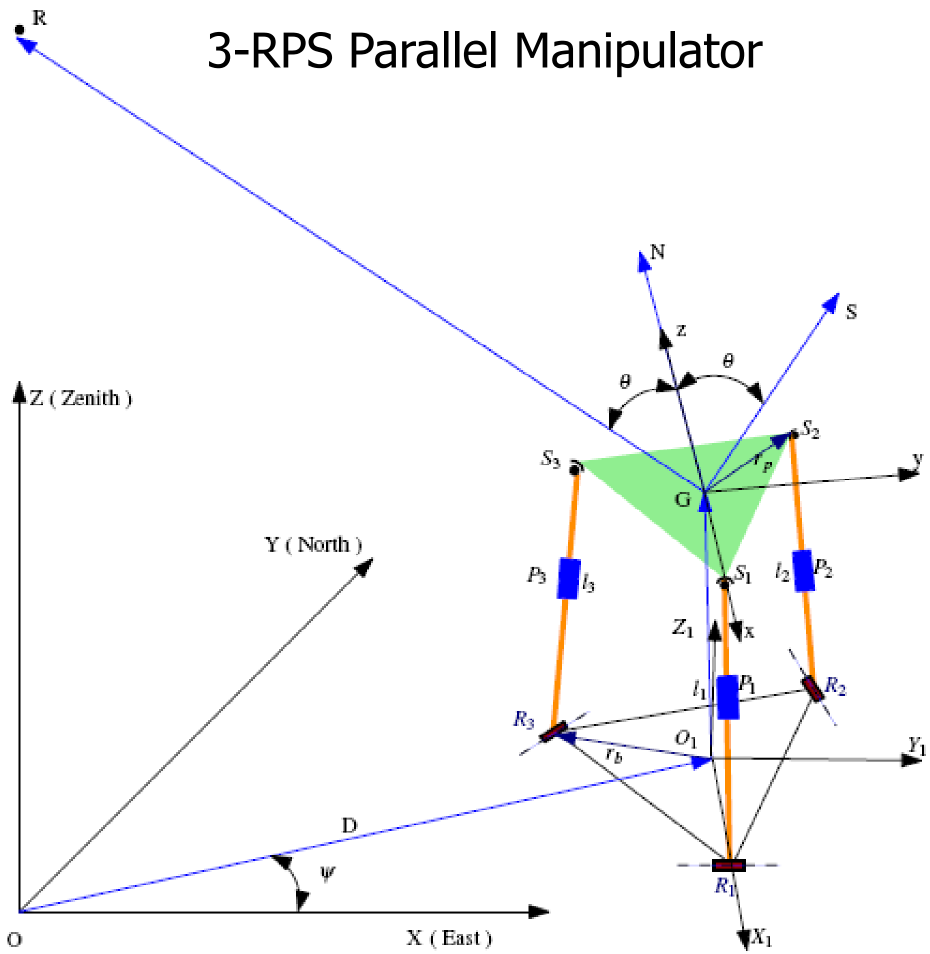
- Need large amount of backing/support material for avoiding deflection

- Need accurate and expensive speed reducers to achieve ~15 degrees per hour

L.L. Vant-Hull, Chp.8 - *Central tower concentrating solar power (CSP) systems*

Parallel mechanism for Sun Tracking

3-RPS Parallel Manipulator



- Many advantages as a parallel manipulator

  → More load carrying capacity

  -- can carry larger mirrors

  -- less deflection and hence less use of structural supporting material

  → More accuracy

- Can use linear actuators – no need for expensive speed reducers
- One extra actuator → redundant

  3 principal motion – rot(X),rot(Y) and tran(Z)

  Keep Z_c constant

Ashith Shyam R B

3-RPS Manipulator (Contd.)

Kinematics of 3-RPS

- Given location of sun in the sky, obtain
  a) Orientation of plane of top platform (mirror)
  b) Translations of prismatic joints to achieve the orientation

Algorithm

1) Choose z_c arbitrarily
2) From laws of reflection $\overrightarrow{GN} = \dfrac{\overrightarrow{GS}+\overrightarrow{GR}}{||\overrightarrow{GS}+\overrightarrow{GR}||}$
3) Orientation of top platform with respect to bottom plate [***n o a***] with

$$n_1^2 + n_2^2 + n_3^2 = 1 \qquad (1)$$

$$o_1^2 + o_2^2 + o_3^2 = 1 \qquad (2)$$

$$n_1 a_1 + n_2 a_2 + n_3 a_3 = 0 \qquad (3)$$

$$n_1 o_1 + n_2 o_2 + n_3 o_3 = 0 \qquad (4)$$

$$o_1 a_1 + o_2 a_2 + o_3 a_3 = 0 \qquad (5)$$

3-RPS Manipulator (Contd.)

Algorithm (Contd.)

4) 3-RPS configurations introduces 3 additional constraint

$$y_c + n_2 r_p = 0 \quad (6)$$

$$n_2 = o_1 \quad (7)$$

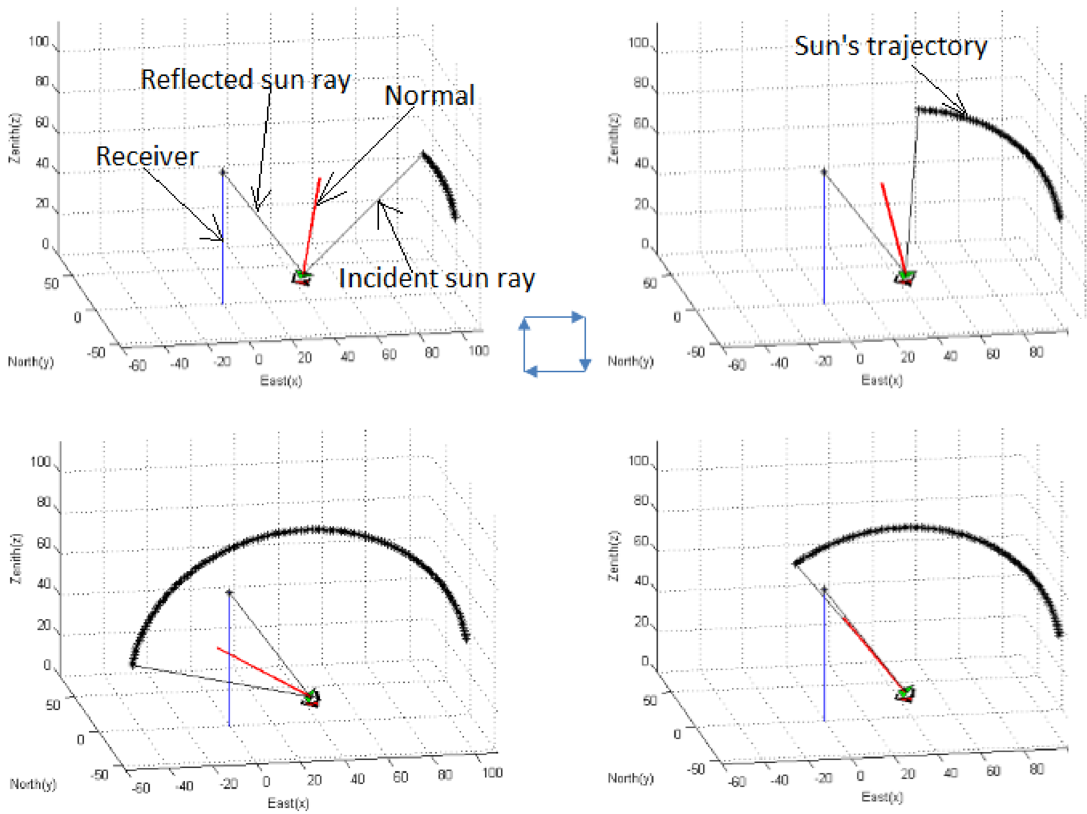
$$x_c = \frac{r_p}{2}(n_1 - o_2) \quad (8)$$

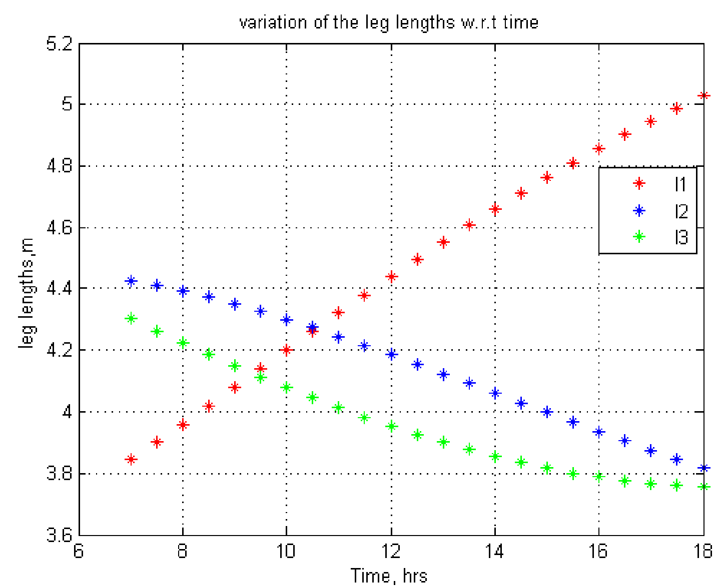
where r_p is the distance from G to S_i

5) 8 equations in 8 unknowns – Use Bezout's elimination to arrive at two equations in two unknowns – x_c and y_c
6) Solve numerically for x_c and y_c
7) Obtain [***n o a***] (rotation matrix) from x_c and y_c

8) From rotation matrix obtain location of S_1, S_2 and S_3 with respect to bottom platform
9) Obtain leg lengths as $l_i = ||\overrightarrow{O_1 R_i} - \overrightarrow{O_1 S_i}||$

3-RPS Manipulator – Simulation results

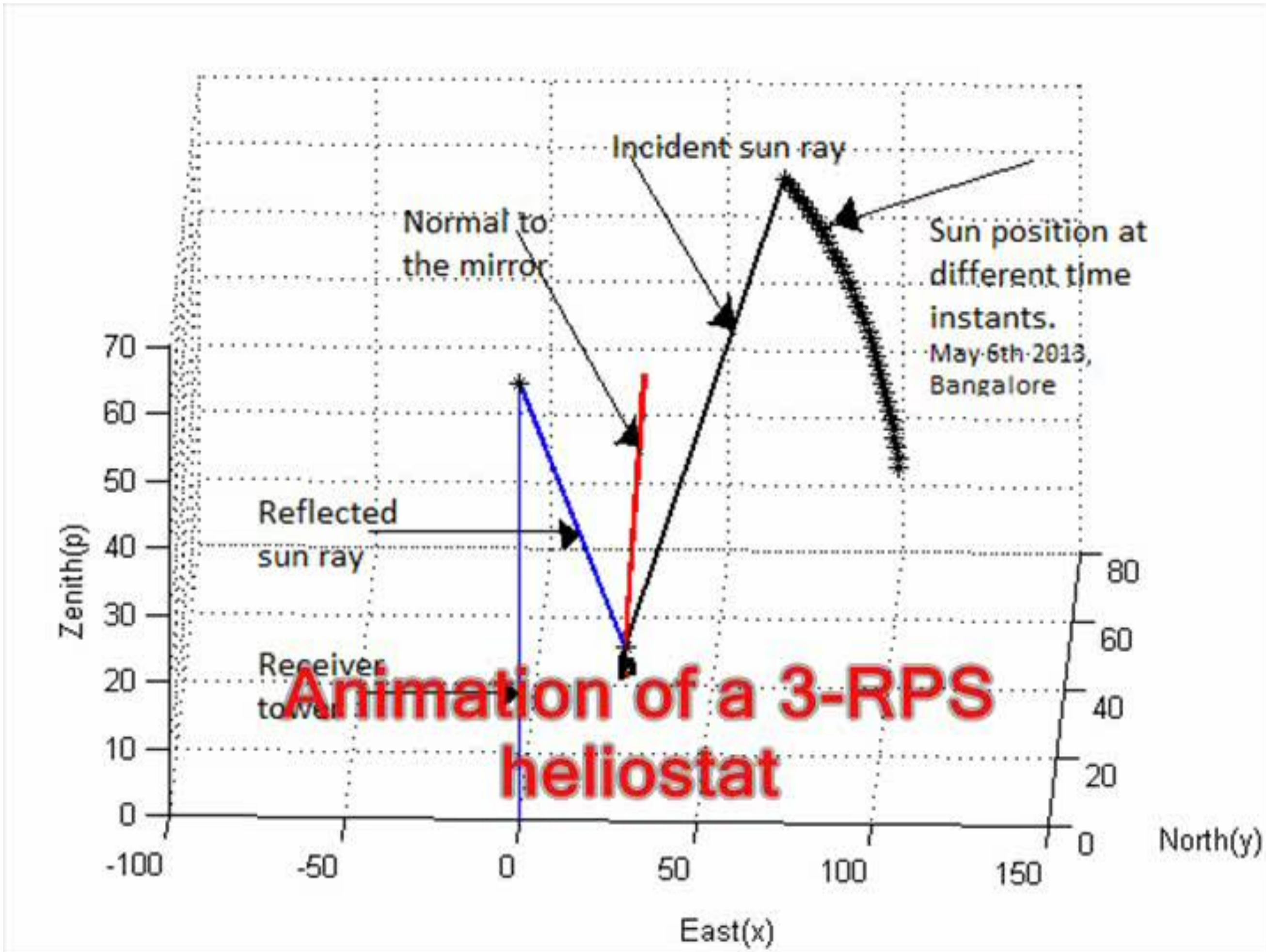




Simulation results for Bangalore, India
May 6, 2013

3-RPS Manipulator – Simulation results

Simulation done in Matlab



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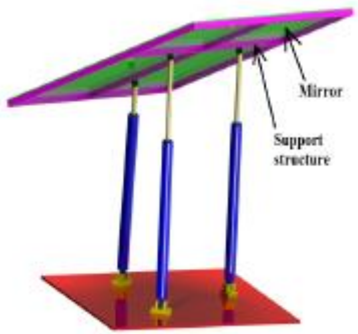
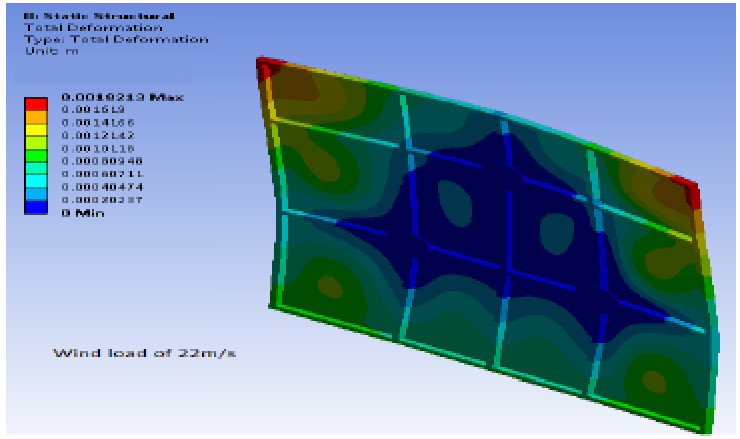
FEA Analysis



(a) CAD model



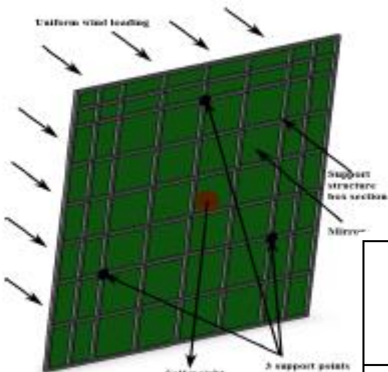
(b) FEA of 2 x 2 mirror

- CAD Model in SolidWorks
- FEA in ANSYS Work bench
- Loading – Self-weight
  (10 kg/m^2)
  +
  Wind load of 22 m/s

Uniform wind load, $P = \frac{1}{2} C_d \rho v^2 FoS$.

Factor of safety $(FoS) = 2$.

- Worst case analysis



(b) wind load

Wind Speed (v) (m/s)	Frame(m x m)	Az-El			3-RPS		
		Max Deformation (mm)	Stress (x 10^7 Pa)	Weight of frame (kg)	Max Deformation (mm)	Stress (x 10^7 Pa)	Weight of frame (kg)
10	2 x 2	1.8862	3.6076	20.94	1.93	4.156	15
	3 x 3	2.6489	3.9829	53.53	2.45	2.595	45
	5 x 5	4.7360	2.9694	356.97	4.90	2.889	198
22	2 x 2	1.8872	4.6809	41	1.82	5.728	30
	3 x 3	2.8740	4.3612	181.17	2.66	5.518	93
	5 x 5	4.7281	2.5648	1332.54	4.92	5.119	535

Support frame weight reduction of 15-60% reduction for 3-RPS heliostat

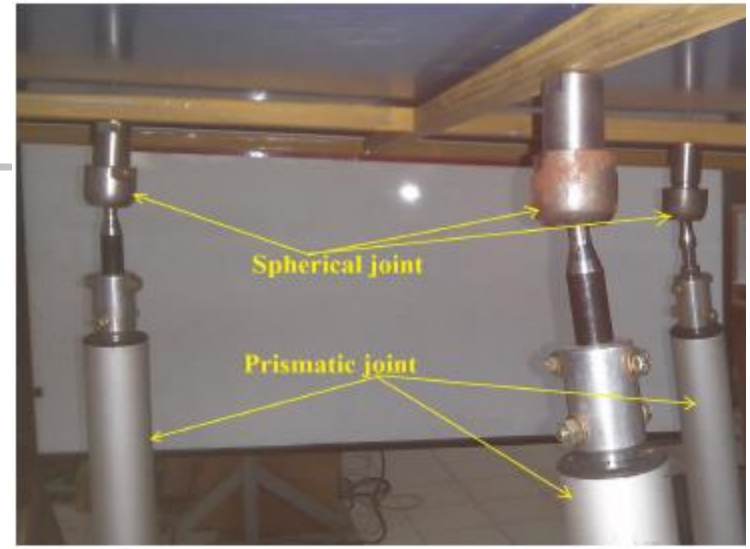
Sun Tracking – Hardware

Azimuth-Elevation Configuration

Ashith & Mohit

Show video

Sun Tracking – Hardware



3-RPS Configuration – Fabricated

Ashith & Mohit

Experimental Results

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Experimental Results (Contd.)

Sun tracking using 3-RPS and Az-El together

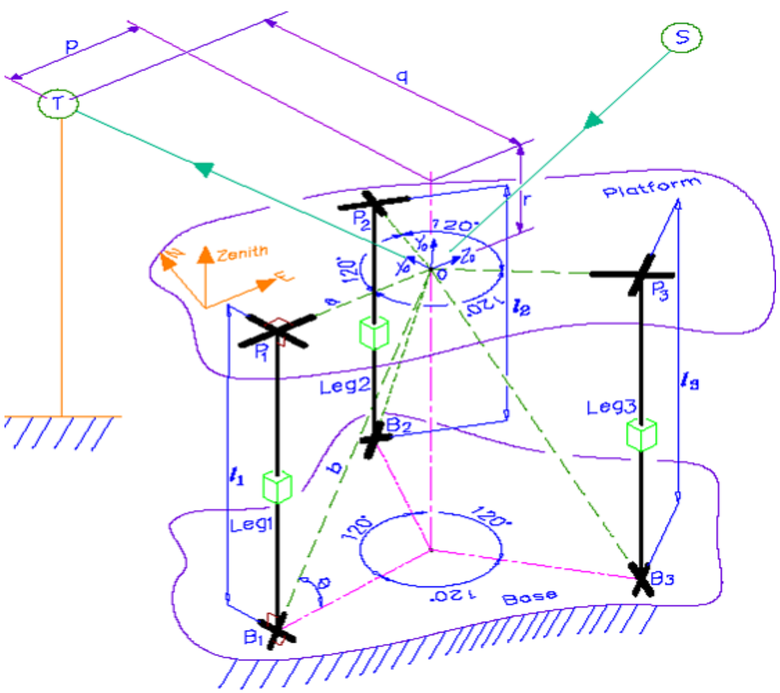
- Sun tracking using Azimuth-Elevation & 3-RPS Heliostat
- Pointing errors larger for 3-RPS ~30 mrad vs ~20 mrad

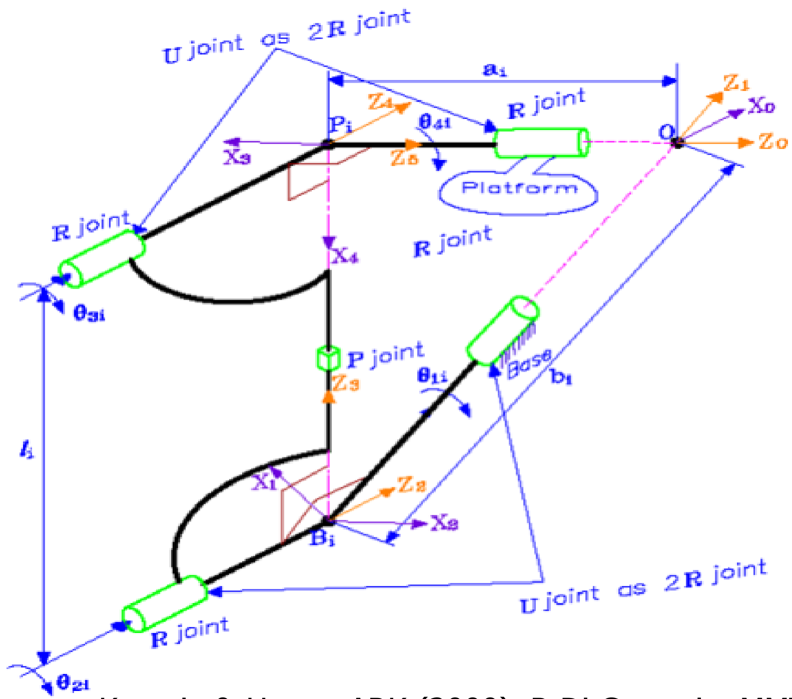
- Main cause – manufacturing & initial settings

Ashith Shyam R B *Solar Energy*

Parallel mechanism for Sun Tracking – 3-UPU Manipulator

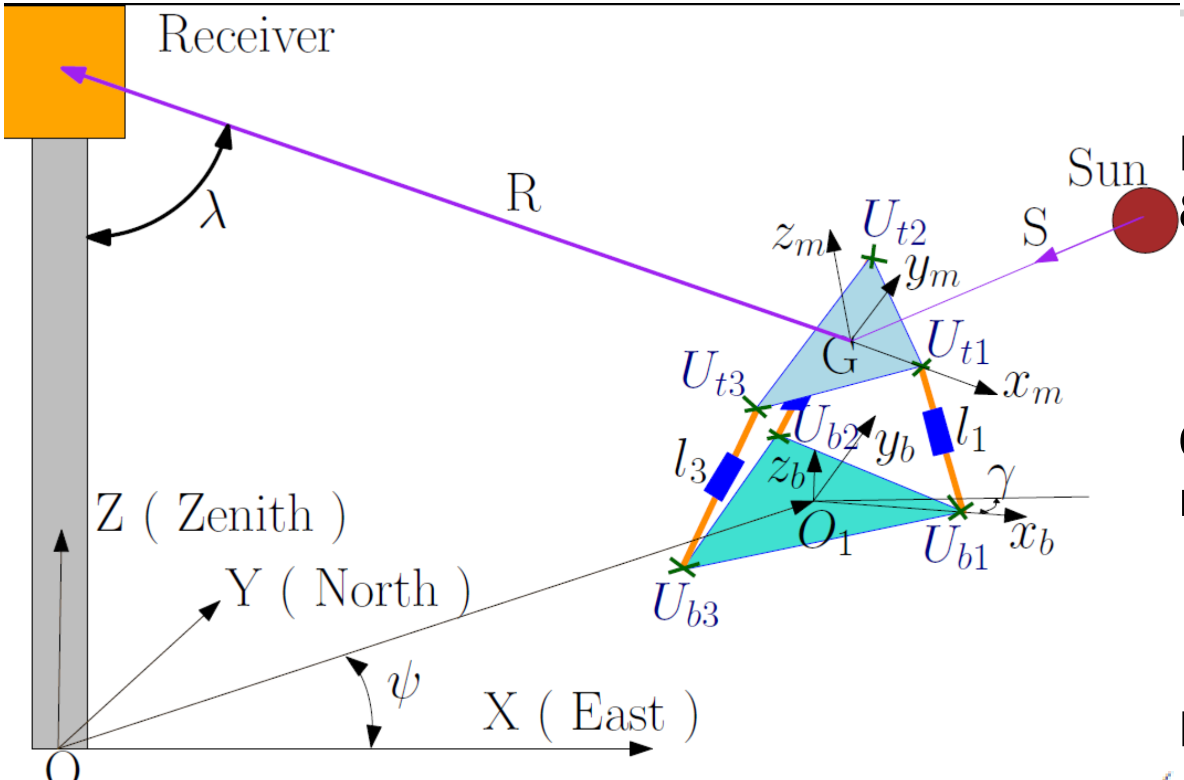
- Three actuators – Prismatic (P) joints & 2 Universal (U) joints in each leg
  → 3 DOF according to Grubler-Kutzbach criterion
- Special axes geometry
  -- Two intermediate R axis are parallel, first and last R axis intersect at a point -- Stationary centre of rotation
- Spherical ``wrist'' – has three rotational degrees of freedom





Karouia & Herve, ARK (2000), R Di Gregorio, MMT (2003)

3-UPU Sun Tracker



From the location of the sun & receiver -- normal to mirror

$$\overrightarrow{GN} = \frac{\overrightarrow{GS} + \overrightarrow{GR}}{||\overrightarrow{GS} + \overrightarrow{GR}||}$$

Orientation of mirror M with respect to base B

$$^{M}_{B}[R] = \begin{bmatrix} n_1 & o_1 & a_1 \\ n_2 & o_2 & a_2 \\ n_3 & o_3 & a_3 \end{bmatrix}$$

Note:

$(a_1, a_2, a_3)^T$ is the mirror normal $\overrightarrow{GN}$

Obtain the other two columns of [R] for Az-El and T-A modes

3-UPU Sun Tracker

3-UPU Parallel Manipulator Kinematics (Contd)

Azimuth-Elevation – two consecutive Euler angles

a) Rotation about Z by azimuth angle θ_{Az}

a) Rotation about y_m by angle $(\frac{\pi}{2} - \theta_{El})$
where elevation angle is θ_{El}

Rotation matrix for Az-El configuration

$$R_{Az-El} = \begin{bmatrix} \cos\theta_{Az}\sin\theta_{El} & -\sin\theta_{Az} & \cos\theta_{Az}\cos\theta_{El} \\ \sin\theta_{Az}\sin\theta_{El} & \cos\theta_{Az} & \sin\theta_{Az}\cos\theta_{El} \\ -\cos\theta_{El} & 0 & \sin\theta_{El} \end{bmatrix}$$

Since the last column $\overrightarrow{GN}$ is known, azimuth and elevation angle can be obtained

3-UPU Sun Tracker

3-UPU Parallel Manipulator Kinematics (Contd)

Rotation matrix for Target-Aligned (T-A) configuration

Two consecutive Euler angles

a) Spin about $\overrightarrow{GR}$ by θ_{sp}

b) Rotate about y_m by elevation angle θ_{el}

Rotation matrix for Spinning-Elevation (T-A)

$$\begin{bmatrix} c_\psi c_\lambda c_{\theta_{sp}} c_{\theta_{el}} - s_\psi s_{\theta_{sp}} c_{\theta_{el}} + c_\psi s_\lambda s_{\theta_{el}} & -c_\psi c_\lambda s_{\theta_{sp}} - s_\psi c_{\theta_{sp}} & c_\psi c_\lambda c_{\theta_{sp}} s_{\theta_{el}} - s_\psi s_{\theta_{sp}} s_{\theta_{el}} - c_\psi s_\lambda c_{\theta_{el}} \\ s_\psi c_\lambda c_{\theta_{sp}} c_{\theta_{el}} + c_\psi s_{\theta_{sp}} c_{\theta_{el}} + s_\psi s_\lambda s_{\theta_{el}} & -s_\psi c_\lambda s_{\theta_{sp}} + c_\psi c_{\theta_{sp}} & s_\psi c_\lambda c_{\theta_{sp}} s_{\theta_{el}} + c_\psi s_{\theta_{sp}} s_{\theta_{el}} - s_\psi s_\lambda c_{\theta_{el}} \\ s_\lambda c_{\theta_{sp}} c_{\theta_{el}} - c_\lambda s_{\theta_{el}} & -s_\lambda s_{\theta_{sp}} & s_\lambda c_{\theta_{sp}} s_{\theta_{el}} + c_\lambda c_{\theta_{el}} \end{bmatrix}$$

Comparing last column $\overrightarrow{GN}$ obtain the two angles

3-UPU Sun Tracker

3-UPU Parallel Manipulator Kinematics (Contd)

Actuation required to achieve orientation of mirror

Location of U joint in bottom platform

$$\overrightarrow{O_1U_{b1}} = (r_b, 0, 0)^T$$
$$\overrightarrow{O_1U_{b2}} = (-\frac{1}{2}r_b, \frac{\sqrt{3}}{2}r_b, 0)^T$$
$$\overrightarrow{O_1U_{b3}} = (-\frac{1}{2}r_b, -\frac{\sqrt{3}}{2}r_b, 0)^T$$

Location of U joint in the top platform

$$\overrightarrow{GU_{t1}} = (r_p, 0, 0)^T$$
$$\overrightarrow{GU_{t2}} = (-\frac{1}{2}r_p, \frac{\sqrt{3}}{2}r_p, 0)^T$$
$$\overrightarrow{GU_{t3}} = (-\frac{1}{2}r_p, -\frac{\sqrt{3}}{2}r_p, 0)^T$$

Position vector of top U joint from rotation matrix [R] and translation vector

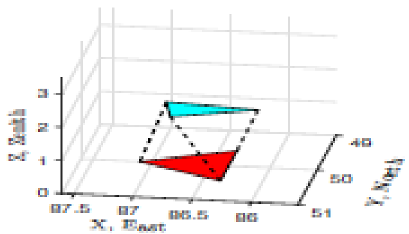
$$\begin{bmatrix} \overrightarrow{O_1U_{ti}} \\ 1 \end{bmatrix} = [T] \begin{bmatrix} \overrightarrow{GU_{ti}} \\ 1 \end{bmatrix}$$

Obtain leg lengths from $l_i = ||\overrightarrow{O_1U_{bi}} - \overrightarrow{O_1U_{ti}}||, \quad i = 1, 2, 3$

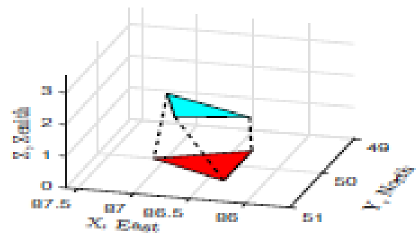
3-UPU Sun Tracker

3-UPU Parallel Manipulator Kinematics (Contd)

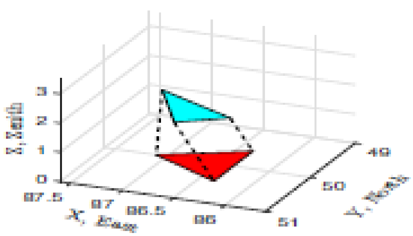
Actuation required to achieve orientation of mirror
March Equinox at Bangalore, India



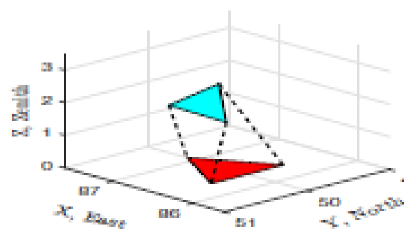
(a) 9 am



(b) 12 noon

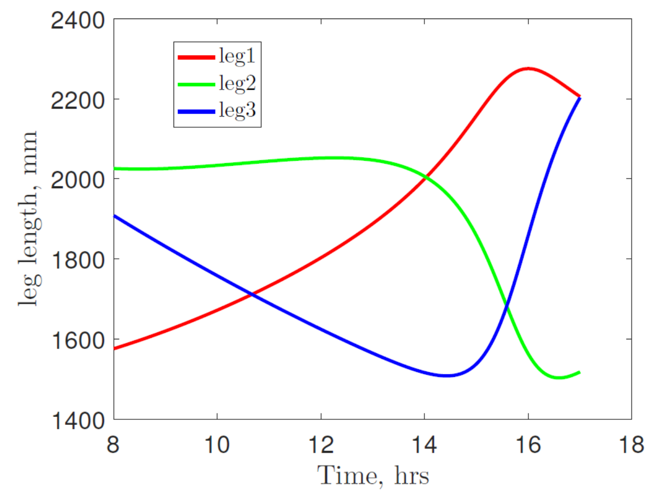


(c) 2 pm



(d) 5 pm

Configuration of 3-UPU in T-A mode



Leg lengths in T-A mode

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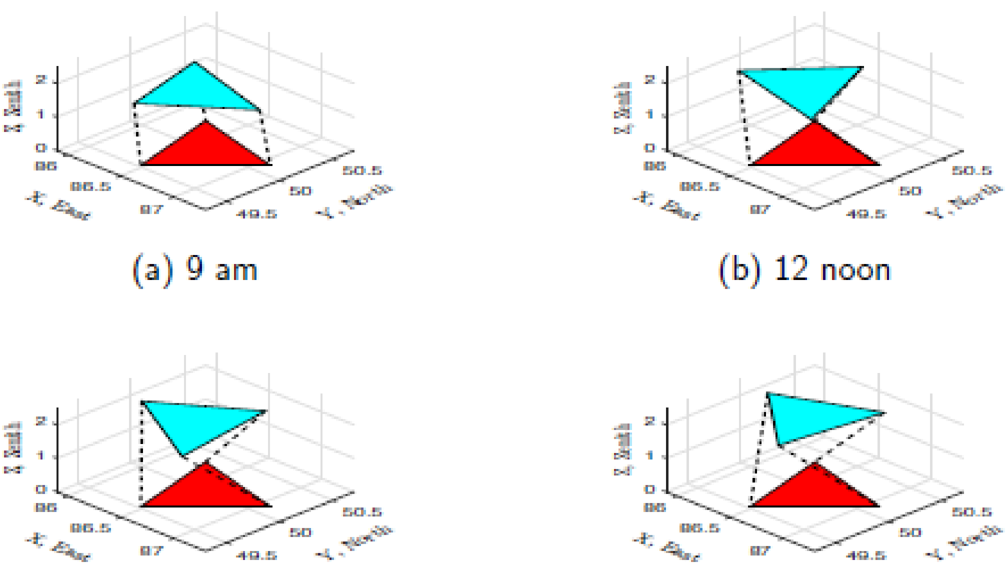
3-UPU Sun Tracker

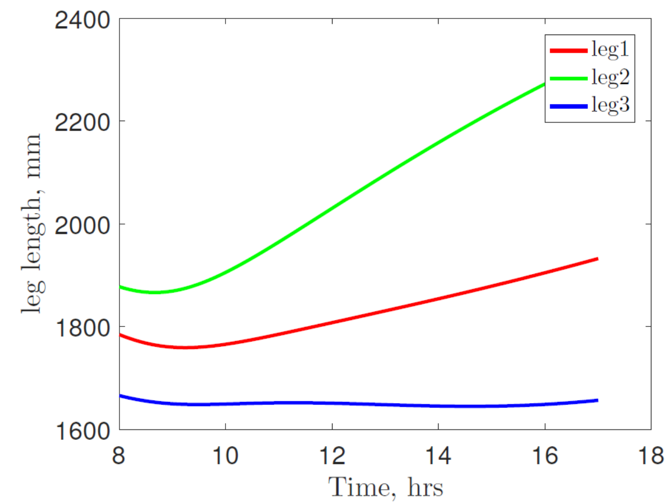
3-UPU Parallel Manipulator Kinematics (Contd)

Actuation required to achieve orientation of mirror
March Equinox at Bangalore, India



(a) 9 am (b) 12 noon (c) 2 pm (d) 5 pm

Configuration of 3-UPU in Az-El mode



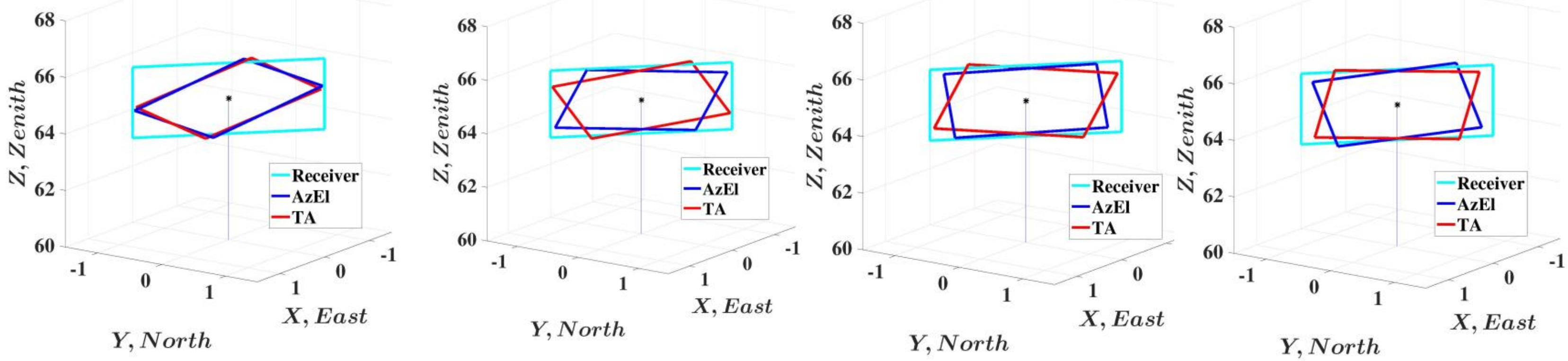
Leg lengths in Az-El mode

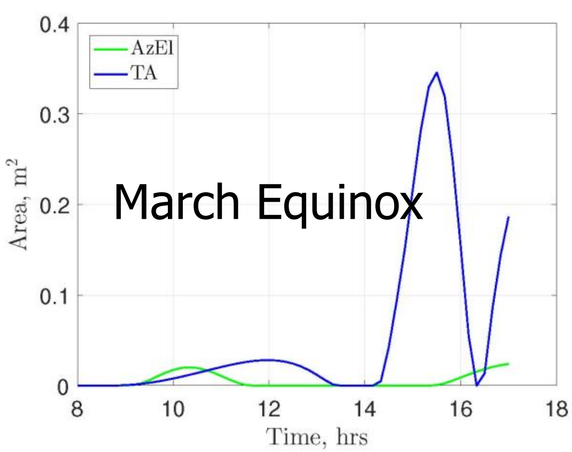
Ashith Shyam R B *MMT*

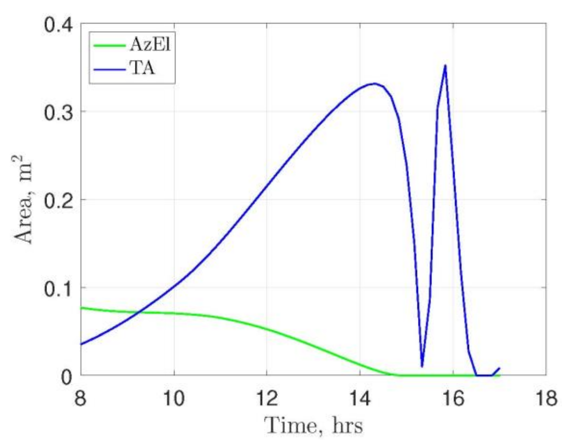
Sun Tracking using Az-EL & T-A

Spillage losses – image of plane mirror on a receiver during March Equinox

(a) 9 am (b) 12 noon (c) 2 pm (d) 5 pm







December Solstice

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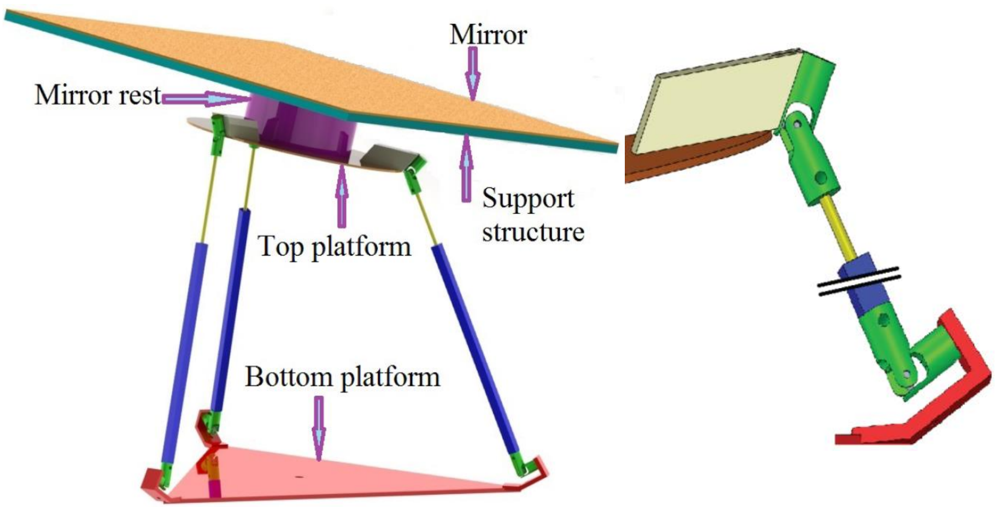
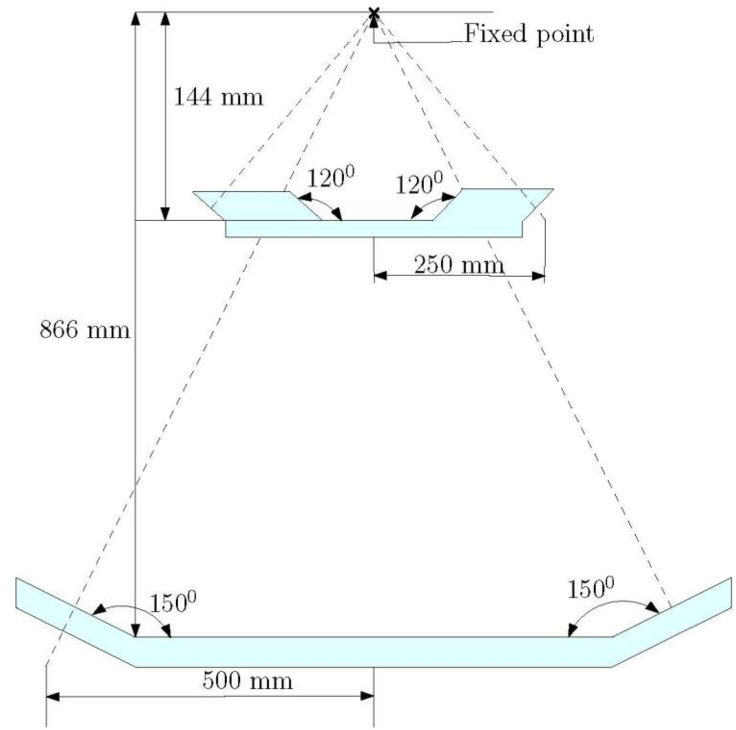
3-UPU Sun Tracker

3-UPU Parallel Manipulator





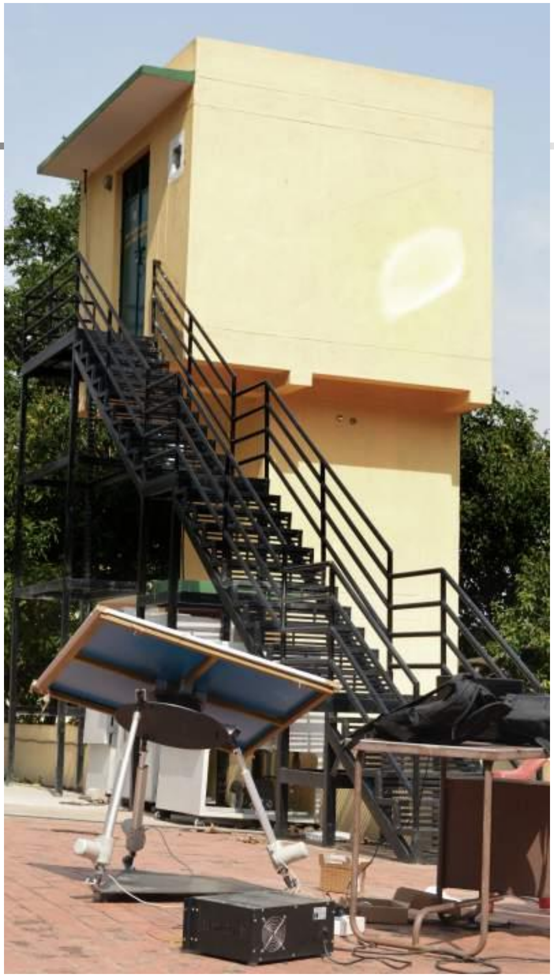
CAD model of 3-UPU ``wrist" and leg details

Centre of rotation is above the plane of the mirror

Sun Tracking using 3-UPU

- Switched between for Az-El or Target-Aligned configurations
- e-Reconfigurable – no change in hardware
- Experiments done at IISc

3-UPU as TA and Az-EL



Bangalore @ roof of ICER

May 24, 2017

Receiver centre at
(0, 0 6.72) m

Mirror centre at
(-10, 3, 0) m

Az-El 3:18 pm

T-A 3:20 pm

Ashith Shyam R B *MMT*

Conclusion

- Novel use of a parallel manipulator for sun tracking
- Kinematics & Design Challenges
- Several advantages
  - → More load carrying capacity
  - → Use of low-cost linear actuators
  - → Potentially more accurate
  - → e-Reconfigurable – use of redundant actuation in 3-UPU
- Not really more accurate!
  - → Too much play at the joints
  - → Need better manufacturing

Thank you

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