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Space Robotics

Guidance, Navigation and Control Challenges

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Presentation Outline

- Space manipulators
  - introduction
  - flexible joint control
  - flexible link control

- Mobile robots in Space

- Flying robots

Space manipulators vs Mobile robots

- Manipulators
- Mobile robots (rovers, autonomous ground
- Flying and floating robots (UAV and spacecraft)

Space-based Robots

- ☐ space robotic manipulators
  - o can perform repetitive and lengthy tasks with reduced risk and improved performance
  - o require less infrastructure than manned systems
    - ❖ no life support systems
- ☐ application examples
  - o maintenance, repair, and assembly
  - o spacecraft deployment and retrieval
  - o extravehicular activity support
  - o shuttle inspection

Space-based Robots

- ❑ flexible links and joints
  - o operational control challenges due to flexible effects, especially in the joints
  - o link and joint flexibility effects introduce vibrations that can lead to instability when neglected in the control system design
- ❑ objectives
  - o develop and validate advanced control systems for flexible joint space robotic manipulators

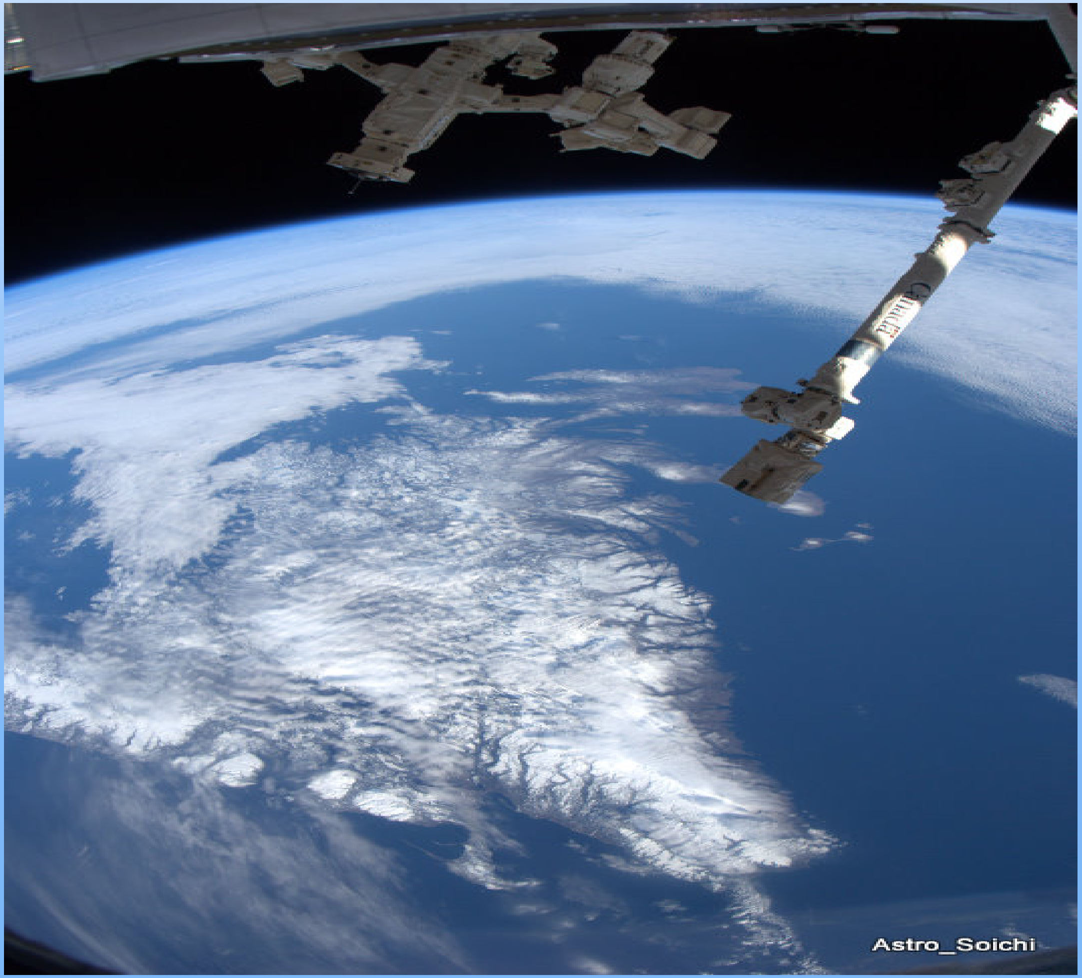
Space-based Robots

- ☐ unresolved issues
  - o simple and efficient algorithms that account for practical limitations have yet to be developed
  - o applicability of existing control strategies to real-time space applications (no gravity, highly limited computational load) needs to be assessed
  - o performance validation should be done with large square trajectories (flexible effects are more noticeable → greater control challenge)

Space-based Robots

- propose 4 control strategies for flexible joint space robots
- compare their respective performance while tracking a 12.6 m x 12.6 m square trajectory
- further Improvements
  - extend for robots with unknown/variable joint stiffness coefficients

RMS, SSRMS and SPDM



http://twicsy.com/i/txBFg

Remote Manipulator System (RMS)

Remote Manipulator System (RMS) Canadarm1 or Shuttle arm

- 15.3 m long
- Weight 408 kg
- Diameter 38 cm
- Payload 29,500 kg

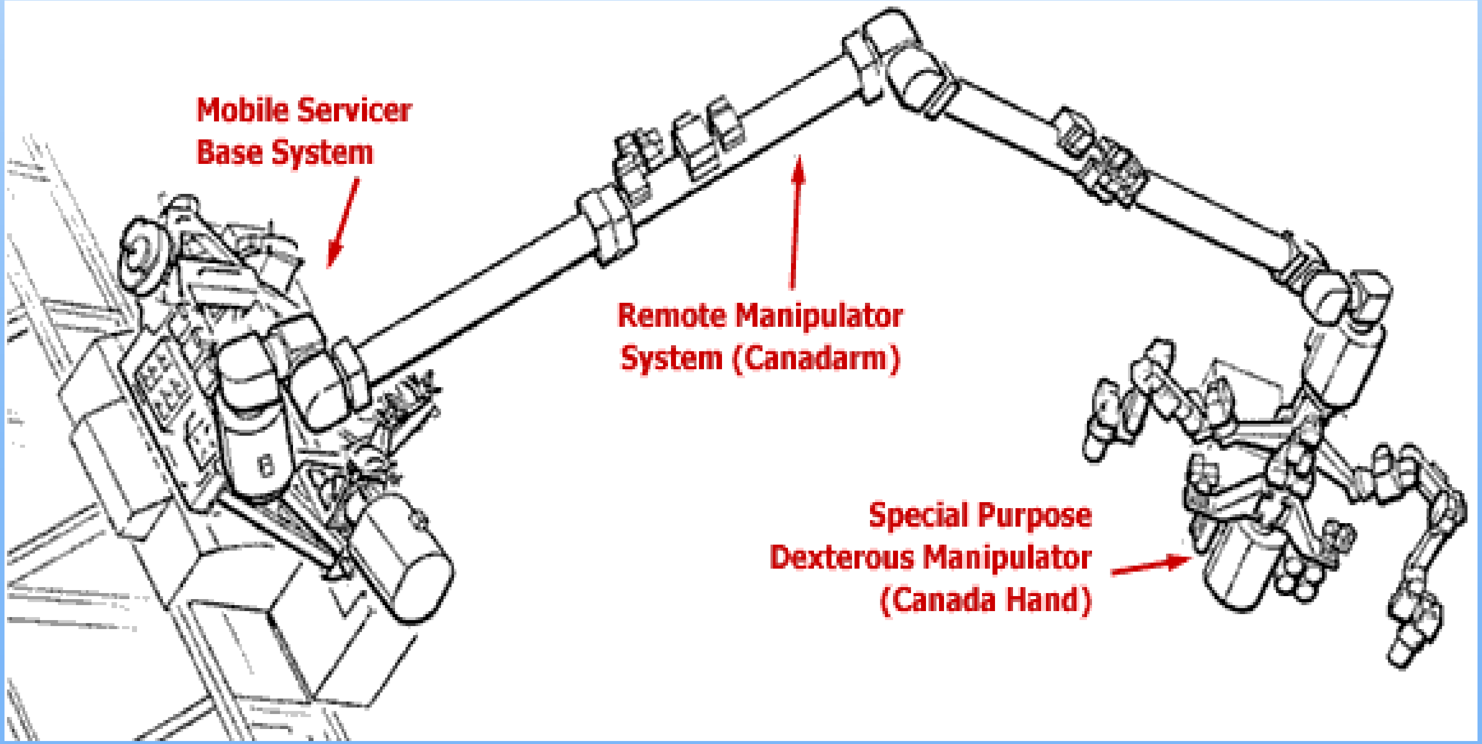
Mobile Servicing System

MBS

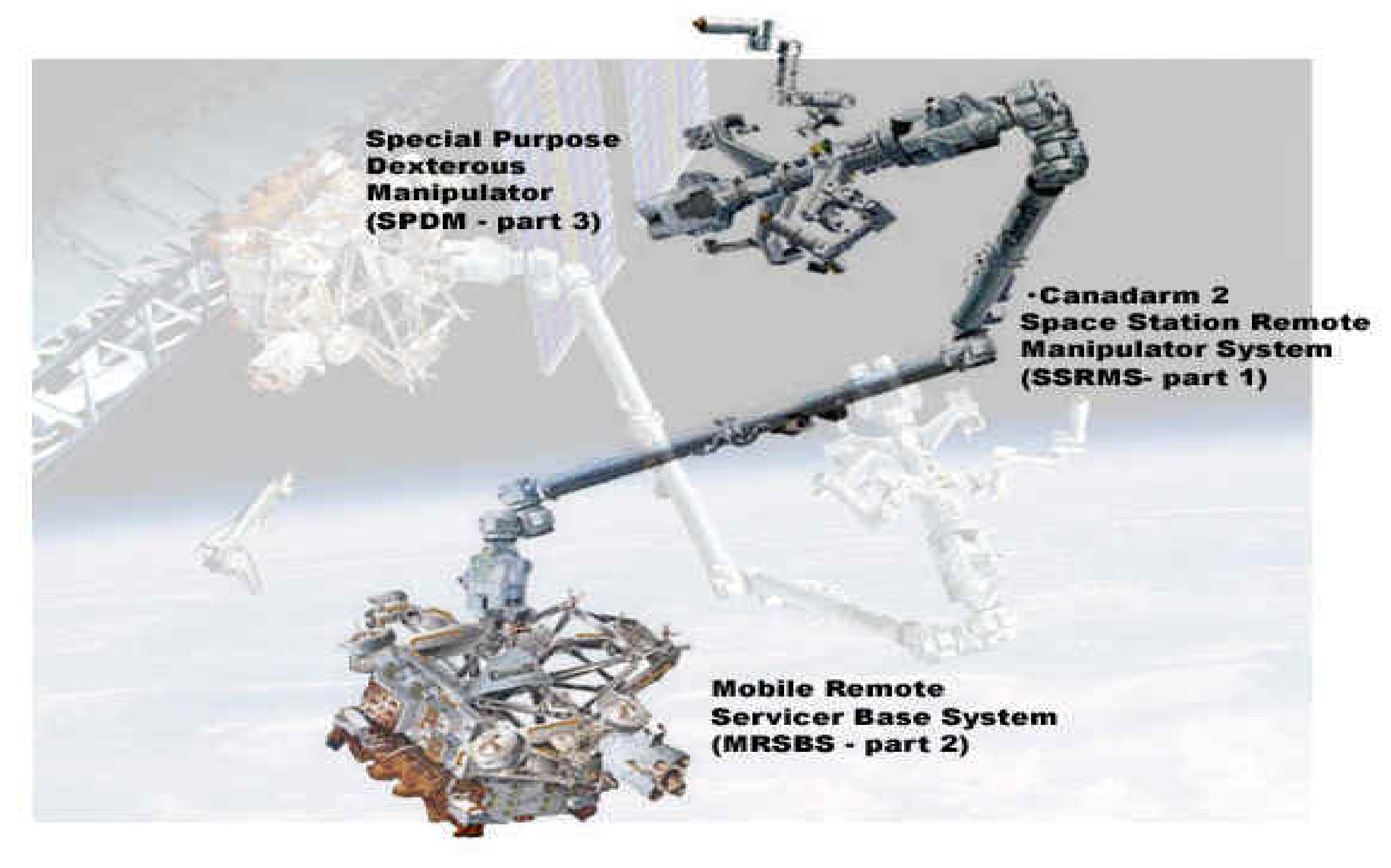
SSRMS

SPDM

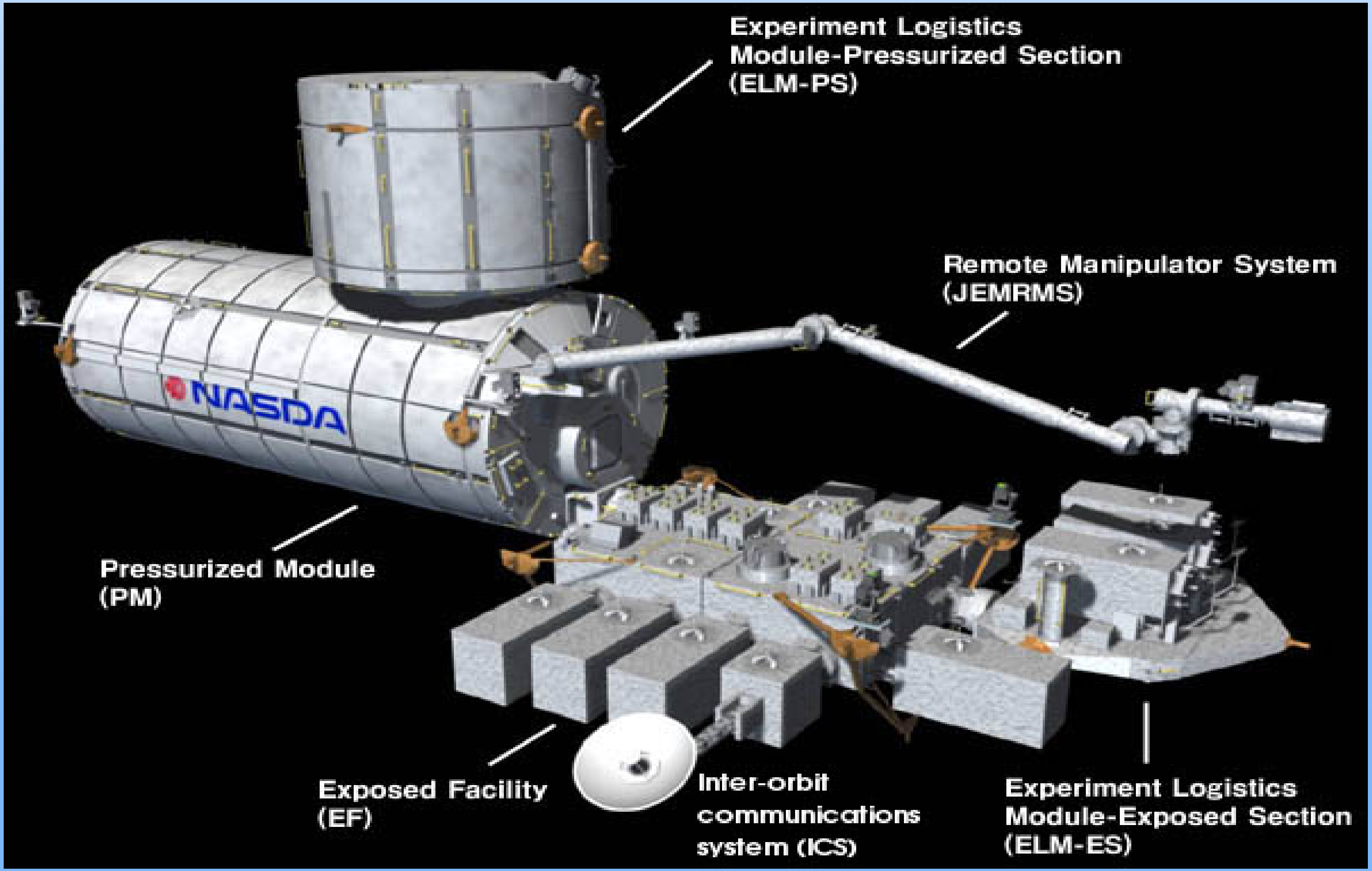
Space Robotic System



Space Robotic System

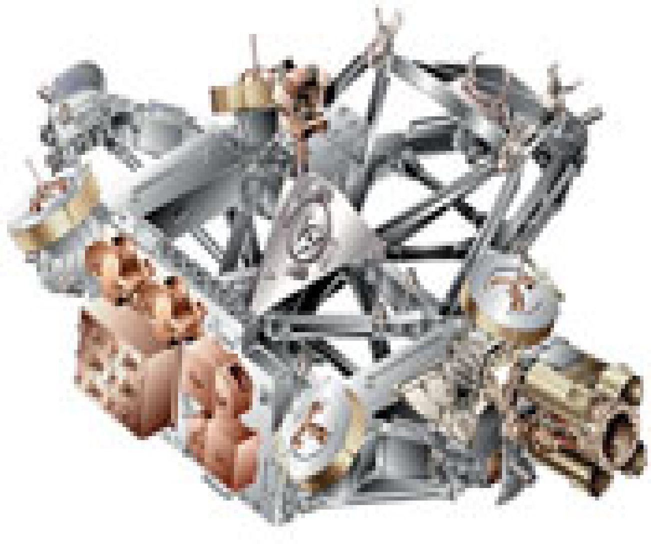


ISS JAXA JEM Module



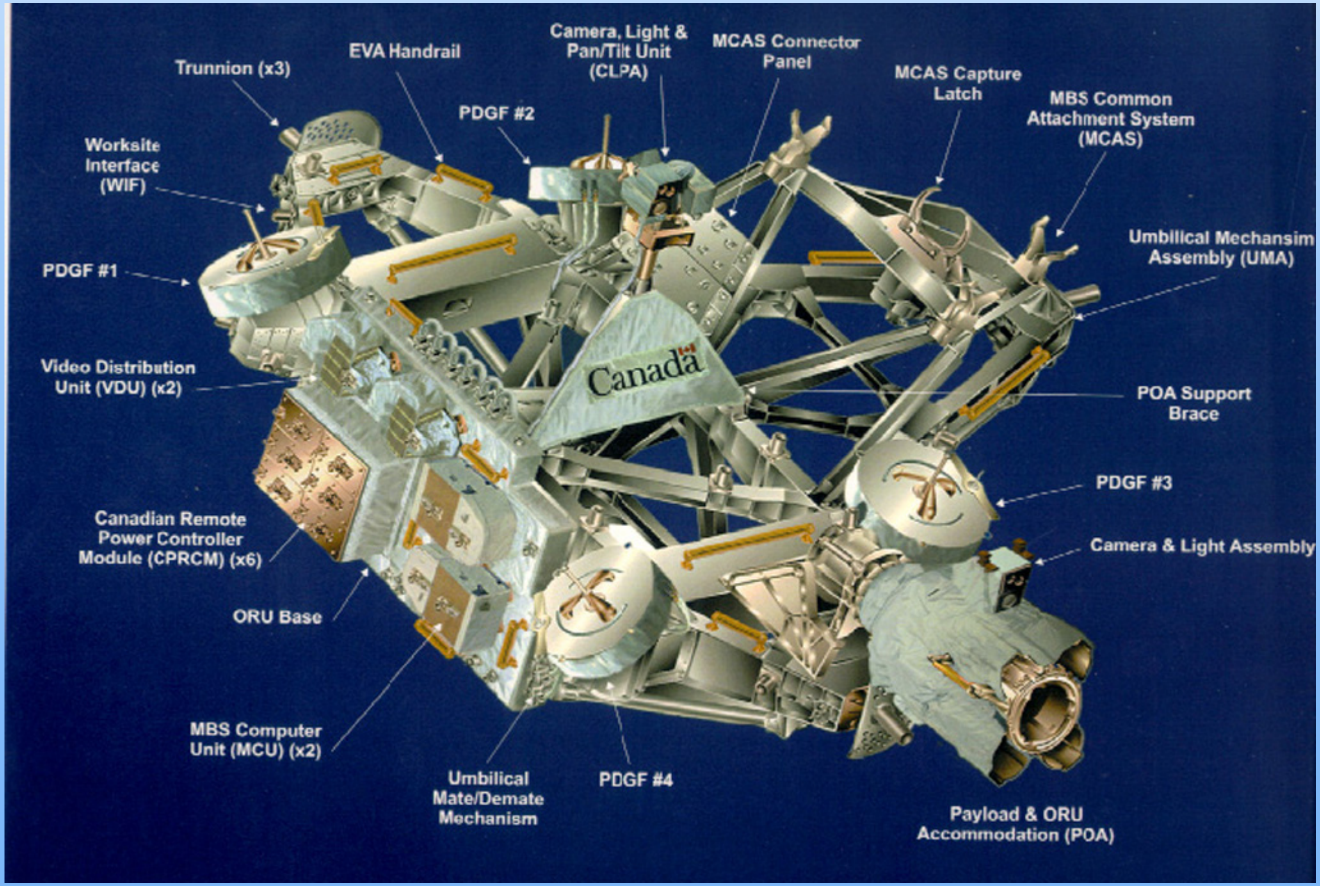
Mobile Base System

- Technical Specs



Total Length	5.7 m x 4.5 m x 2.9 m
Mass (approx)	1,450 kg
Mass Handling/Transportation Capacity	20,900kg
Degrees of Freedom	Fixed
Peak Power (Operational)	825 Watts
Average Power (Keep alive)	365 Watts

Mobile Base Platform (MBS)

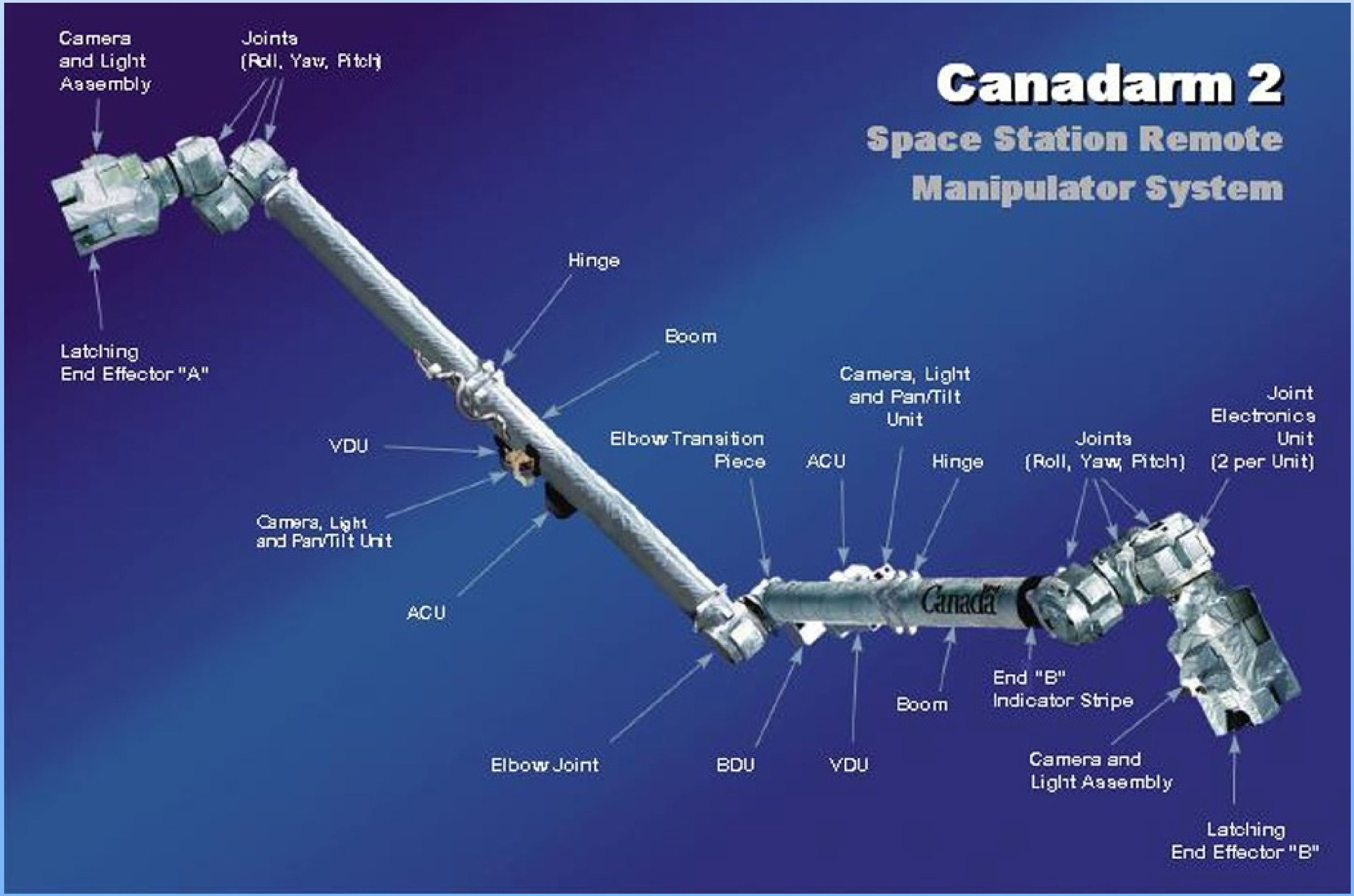


Space Station Remote Manipulator System (SRMS)

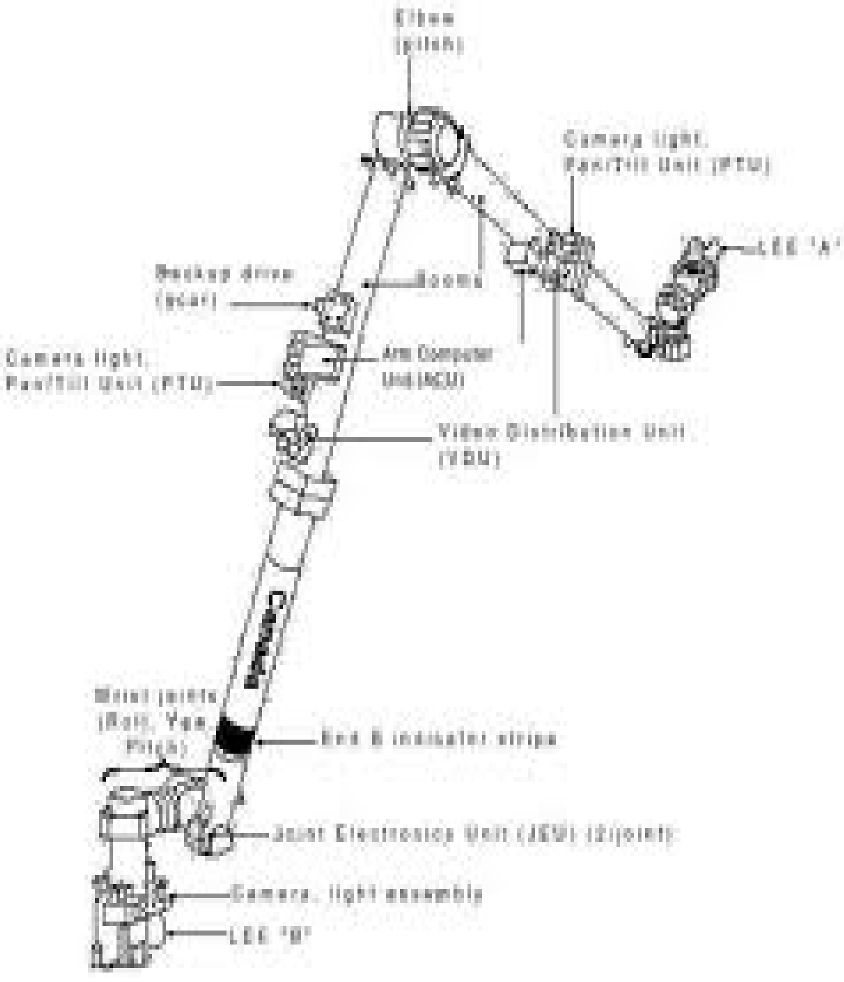
SSRMS Arm Specifications:

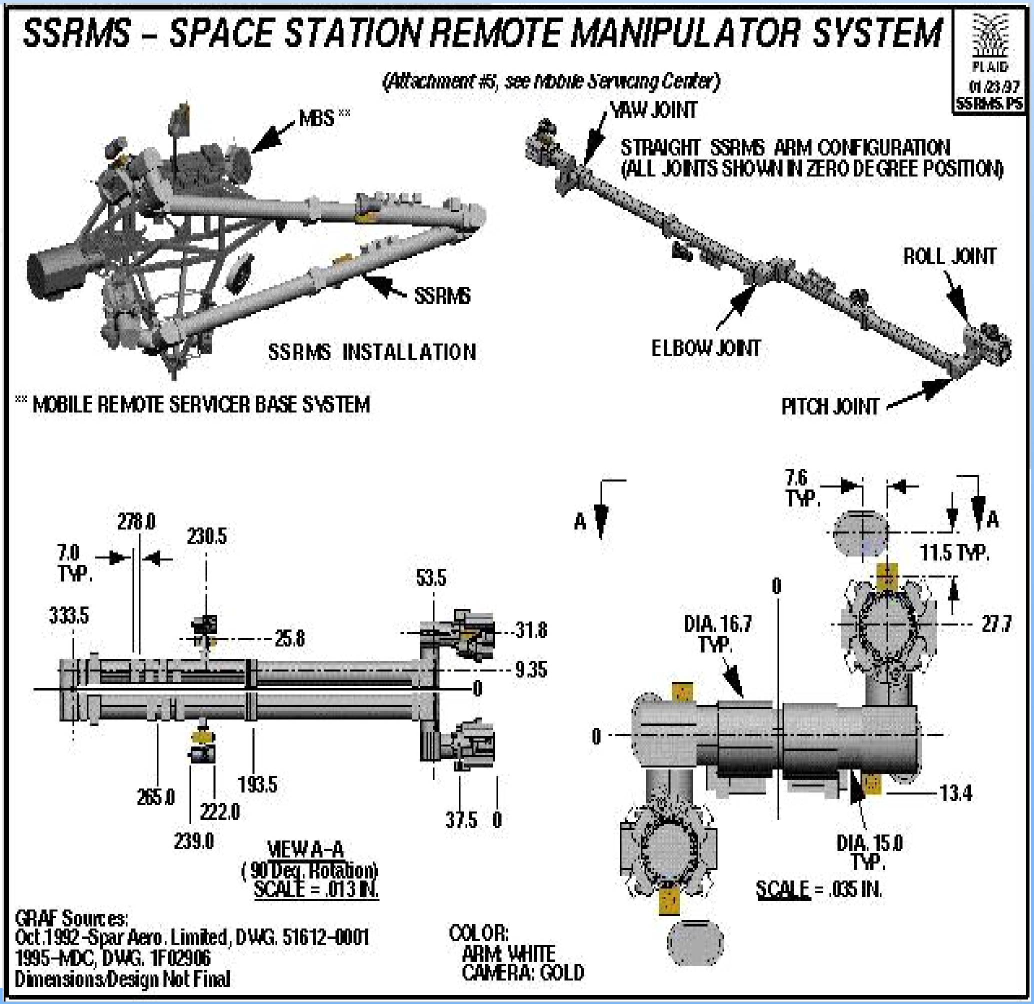
Width 2.2M
Length 17.6M
Mass (approx.) 1,800Kg
Mass handling capacity 100,000Kg
Degrees of freedom 7
Peak power 2000 Watts
Average power 1360 Watts
Stopping distance (max. load) 0.6m

SSRMS

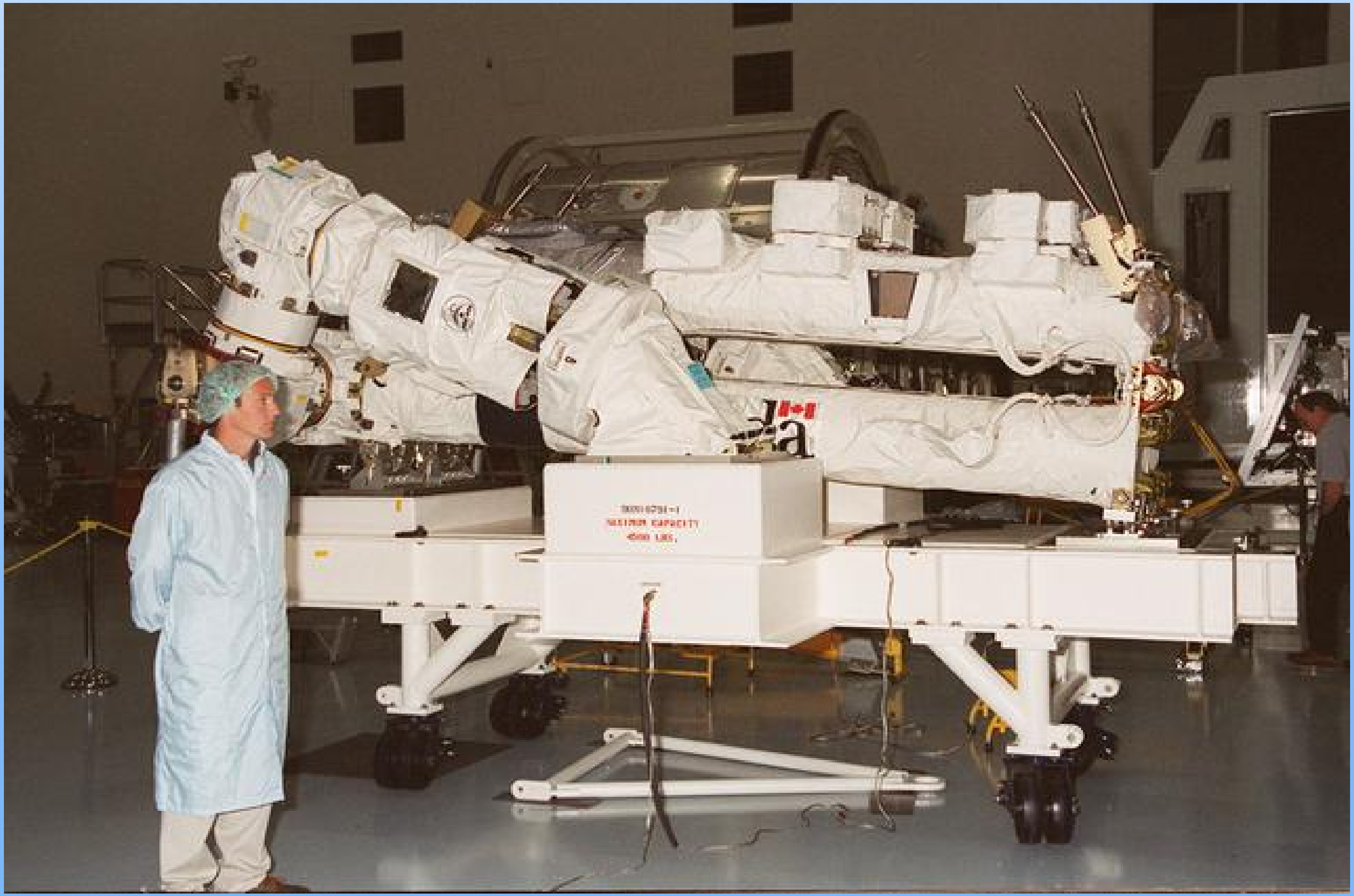

Canadarm 2
Space Station Remote
Manipulator System
Camera and Light Assembly
Joints (Roll, Yaw, Pitch)
Latching End Effector "A"
Hinge
Boom
VDU
Camera, Light and Pan/Tilt Unit
ACU
Elbow Transition Piece
ACU
Camera, Light and Pan/Tilt Unit
Hinge
Joints (Roll, Yaw, Pitch)
Joint Electronics Unit (2 per Unit)
Canada
Elbow Joint
BDU
VDU
Boom
End "B" Indicator Stripe
Camera and Light Assembly
Latching End Effector "B"

Space Station Remote Manipulator System SSRMS

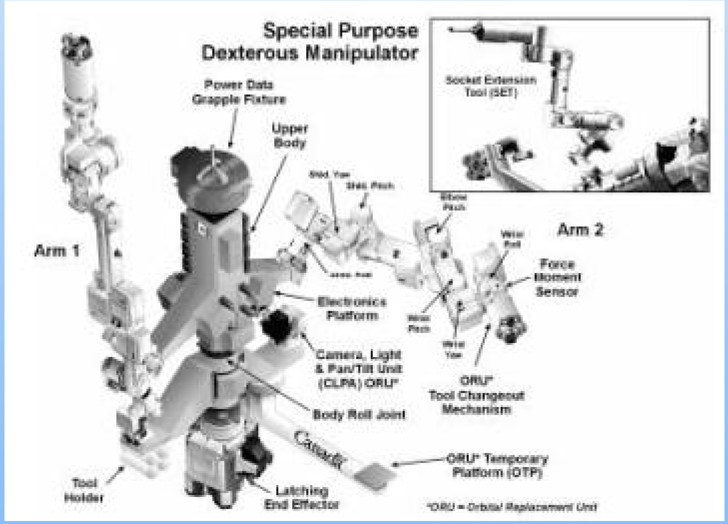




SSRMS folded

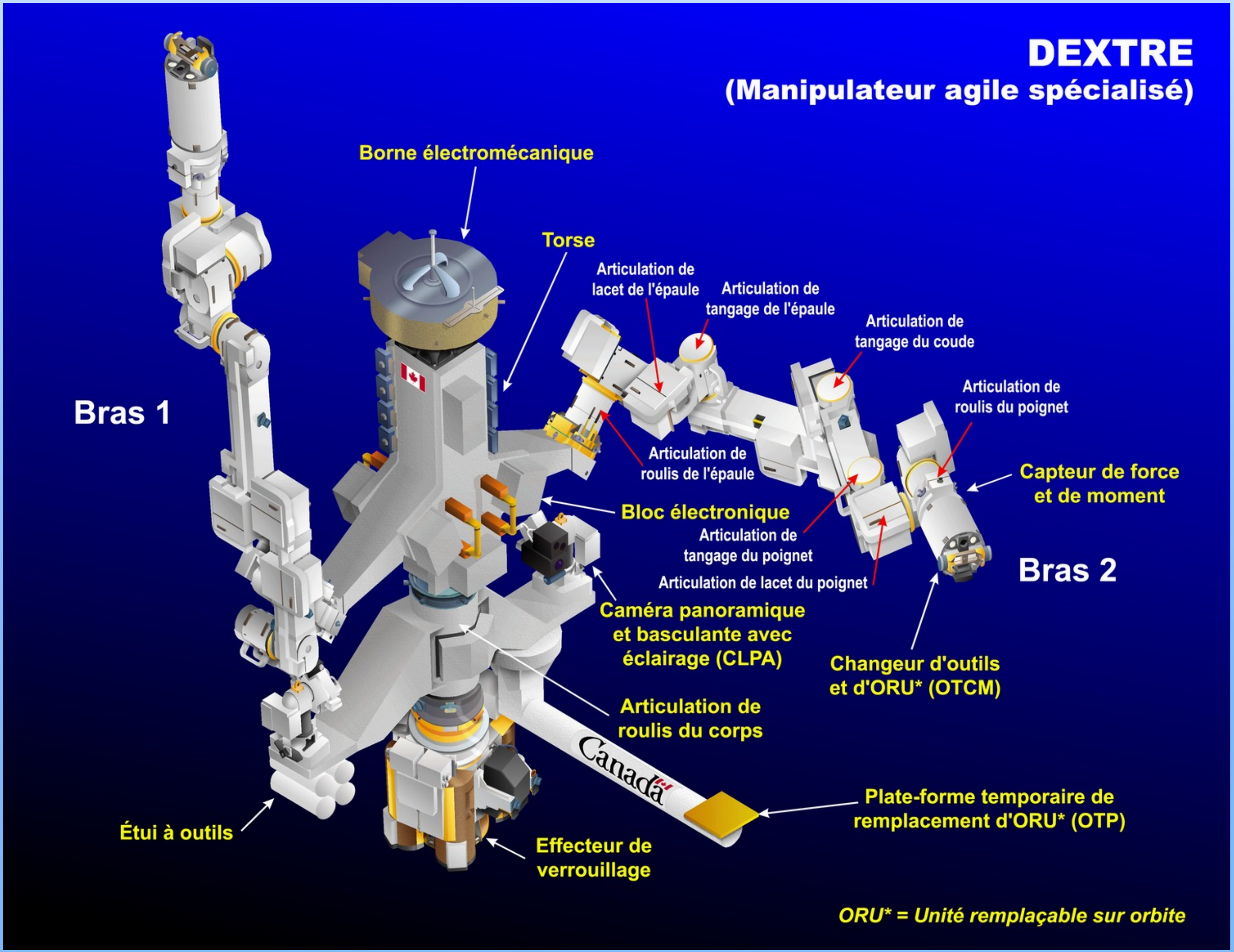


Special Purpose Dextrous Manipulator (SPDM)

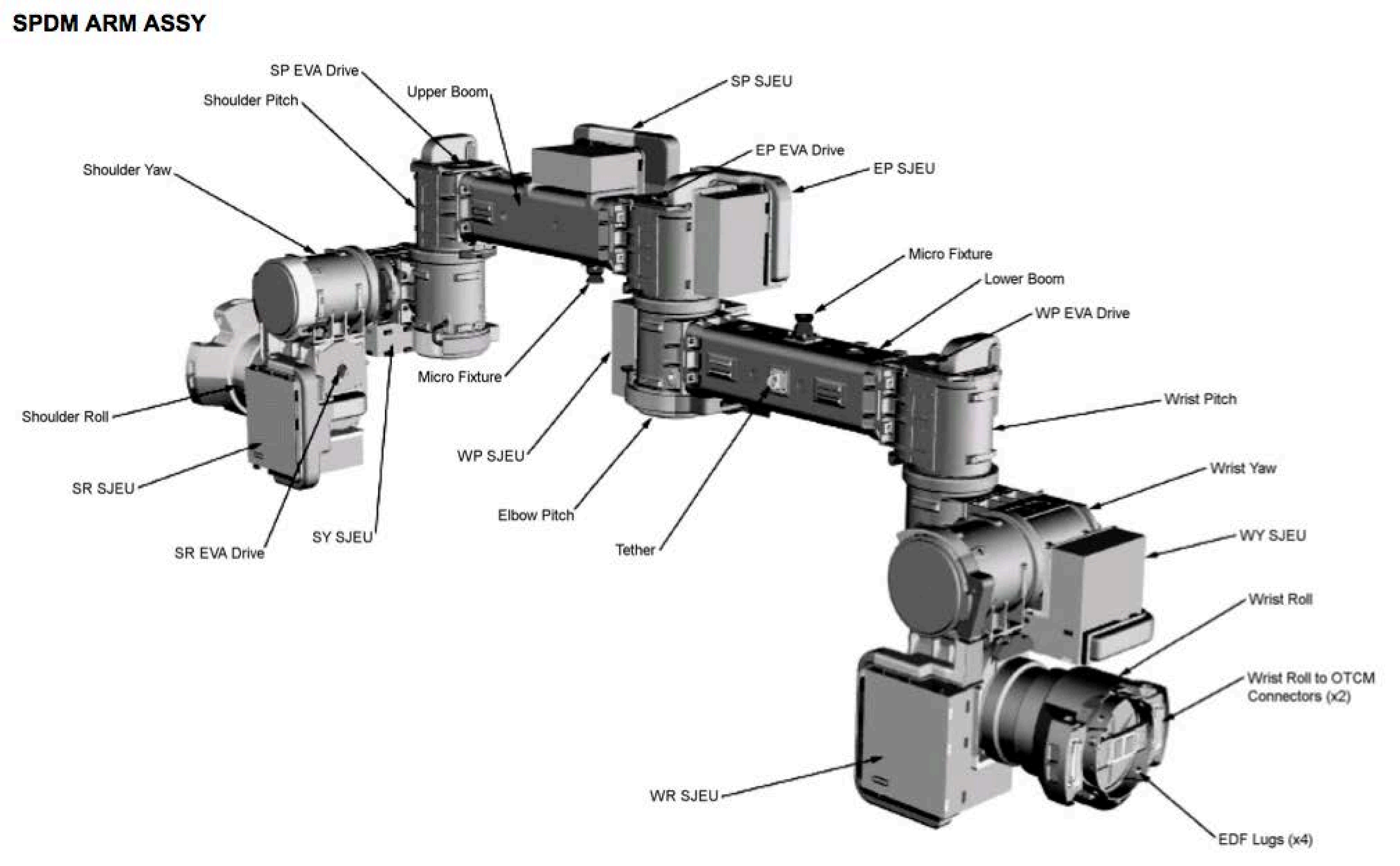


Length	3.5 m
Mass (approx)	1,662 kg
Mass Handling Capacity	600 kg
Degrees of Freedom	15
Peak Power	2000 Watts
Average Power	600 Watts
Stopping Distance (under max. load)	0.15 m

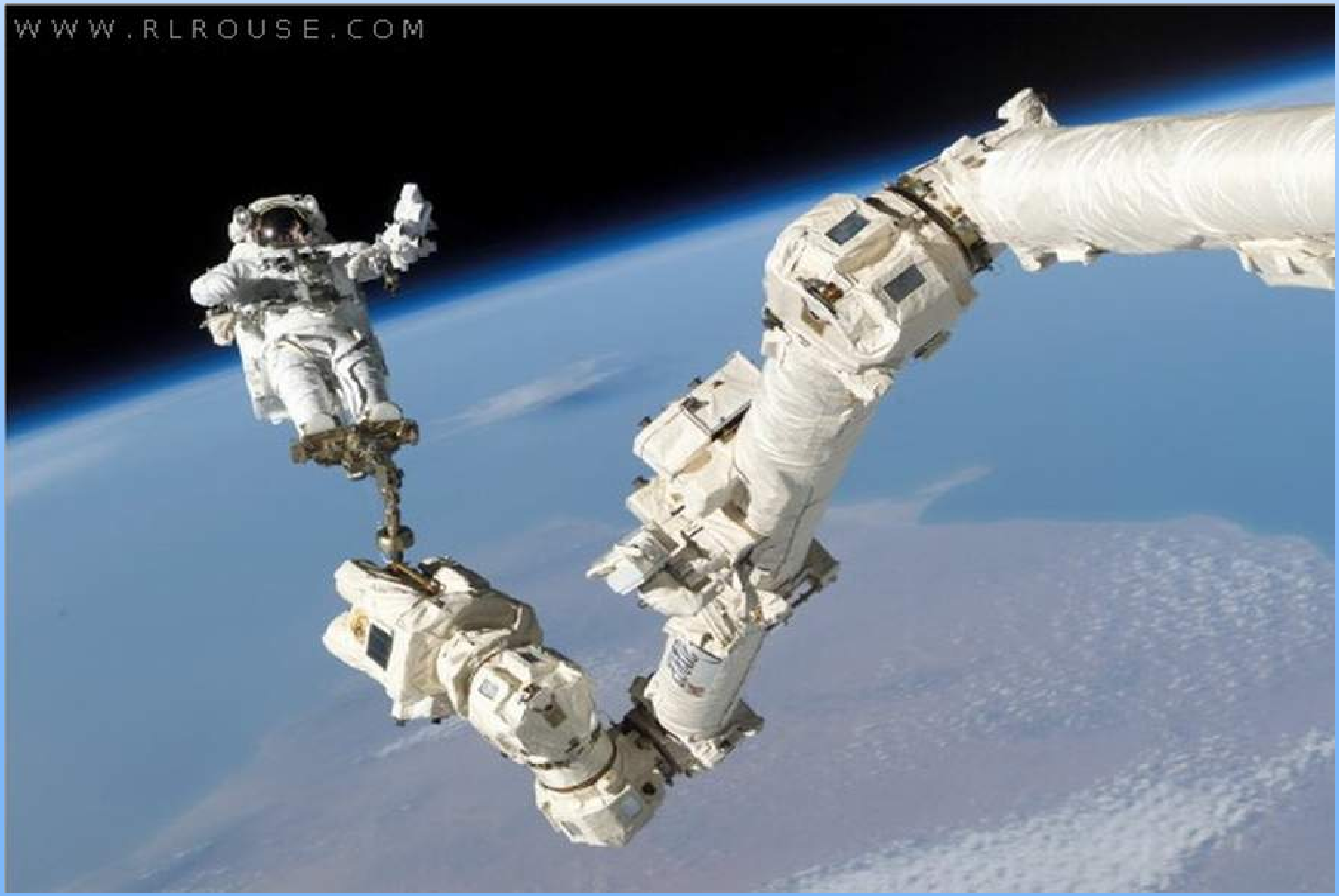
SPDM - Dextre


DEXTRE
(Manipulateur agile spécialisé)
Borne électromécanique
Torse
Articulation de lacet de l'épaule
Articulation de tangage de l'épaule
Articulation de tangage du coude
Articulation de roulis du poignet
Bras 1
Articulation de roulis de l'épaule
Capteur de force et de moment
Bloc électronique
Articulation de tangage du poignet
Articulation de lacet du poignet
Bras 2
Caméra panoramique et basculante avec éclairage (CLPA)
Changeur d'outils et d'ORU* (OTCM)
Articulation de roulis du corps
Canada
Plate-forme temporaire de remplacement d'ORU* (OTP)
Étui à outils
Effecteur de verrouillage
ORU* = Unité remplaçable sur orbite

SPDM


SPDM ARM ASSY
SP EVA Drive
Shoulder Pitch
Upper Boom
SP SJEU
EP EVA Drive
EP SJEU
Shoulder Yaw
Micro Fixture
Lower Boom
WP EVA Drive
Micro Fixture
Wrist Pitch
Shoulder Roll
WP SJEU
Wrist Yaw
SR SJEU
Elbow Pitch
WY SJEU
SY SJEU
Tether
SR EVA Drive
Wrist Roll
Wrist Roll to OTCM Connectors (x2)
WR SJEU
EDF Lugs (x4)

RMS Robot



Shuttle Arm (RMS)

Space Robotics

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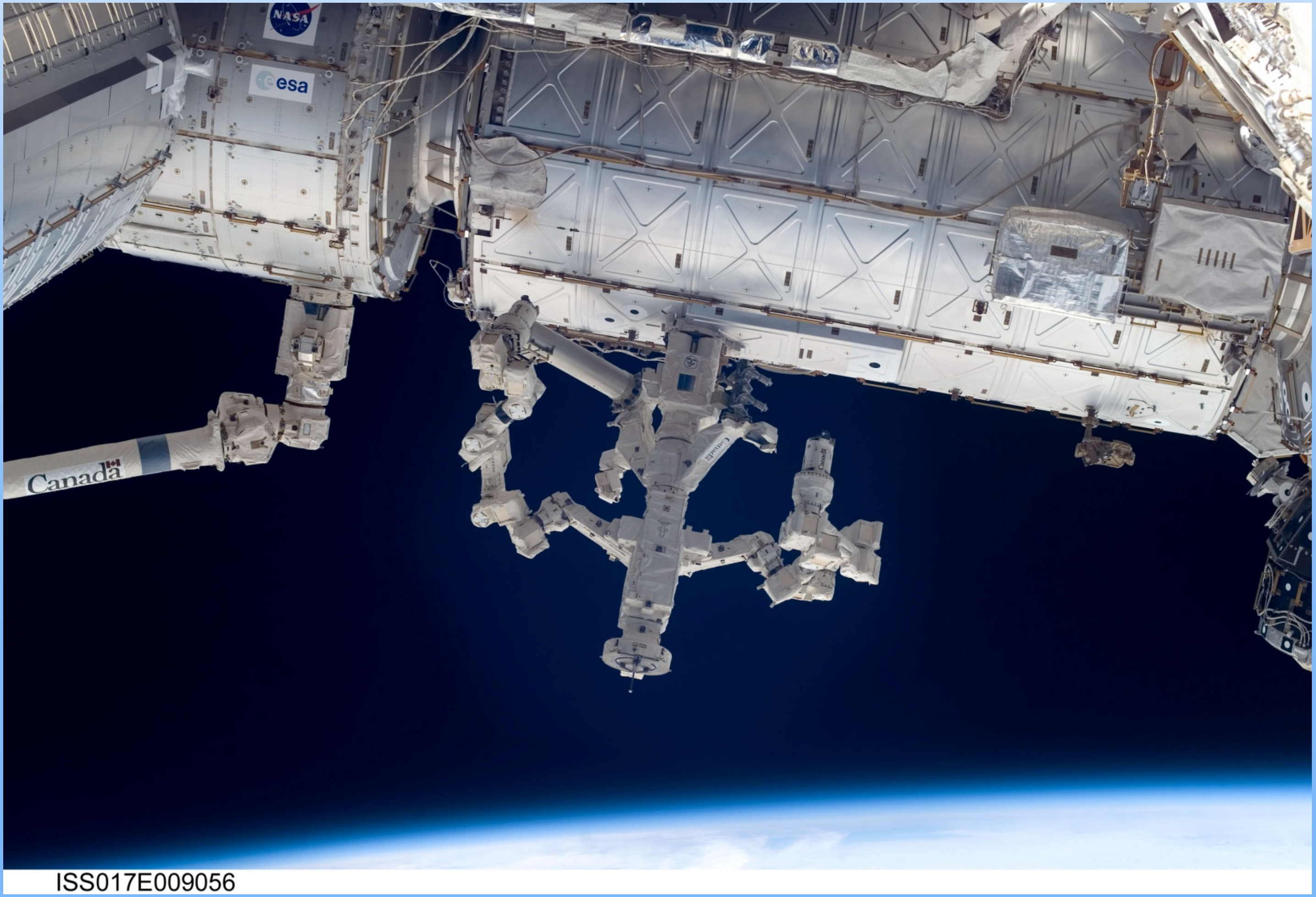

NASA
esa
Canada
ISS017E009056

Space Robotics 3

S123E007088

Satellite retrieval

Satellite robot (SPDM Dextre from CSA) – Tumbling Satellite Problem

Context

- **Space Robotic Manipulators**
  - Represent an ideal technology to perform repetitive and lengthy tasks
  - Require less infrastructure than humans (such as life support systems)

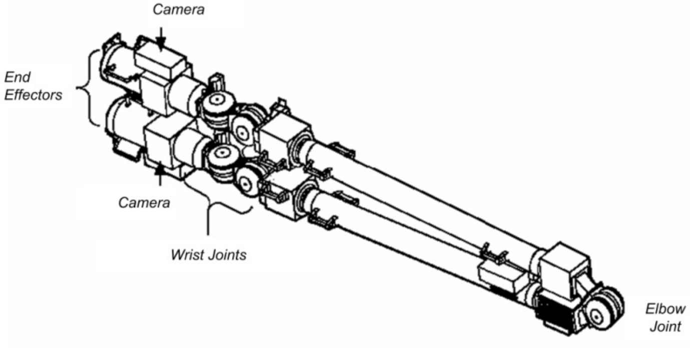


Image courtesy of ESA

- **Application Examples**
  - Maintenance, repair and assembly
  - Spacecraft deployment and retrieve
  - Extravehicular activity support
  - Shuttle inspection

Context

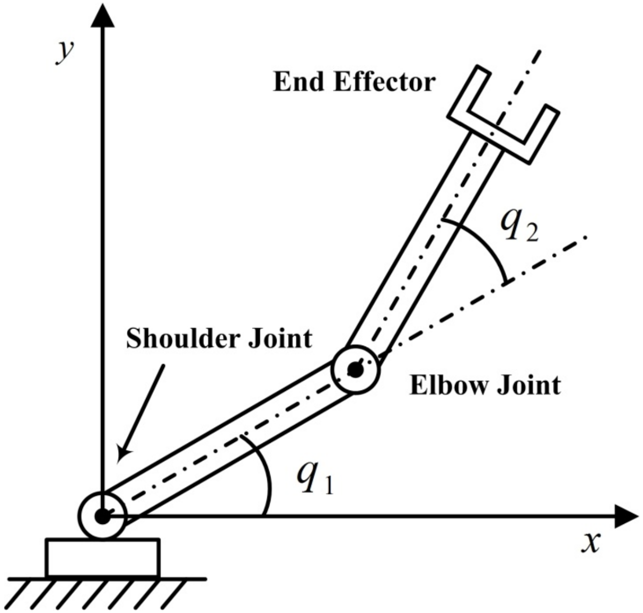
- **Manipulators**
  - Operational control challenges due to flexible effects, especially in the joints
  - Joint flexibility effects introduce vibrations and can lead to instability when neglected in the control system design

- **Main Objective**
  - Develop and validate advanced control systems for flexible joint space robotic manipulators

Two-Link Space Robot

- **Rigid Dynamics**

$$\boldsymbol{\tau} = \mathbf{M}_r(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{C}_r(\mathbf{q},\dot{\mathbf{q}})\dot{\mathbf{q}}$$



where

$$M_{r11} = m_1 l_{c1}^2 + m_2\left(l_1^2 + l_{c2}^2 + 2 l_1 l_{c2}\cos q_2\right) + I_1 + I_2$$

$$M_{r12} = M_{r21} = m_2\left(l_{c2}^2 + l_1 l_{c2}\cos q_2\right) + I_2$$

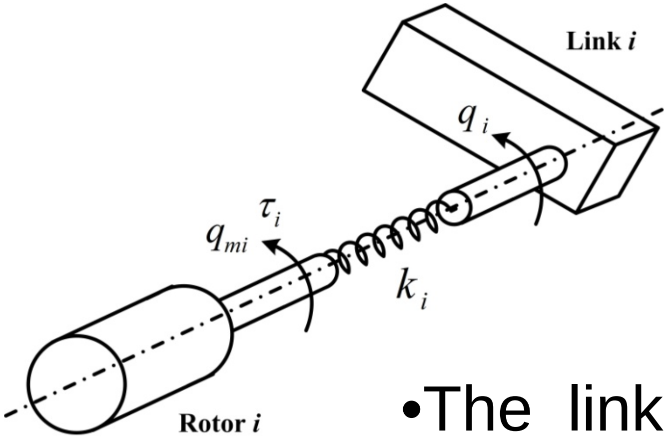
$$M_{r22} = m_2 l_{c2}^2 + I_2$$

and

$$\mathbf{C}_r(\mathbf{q},\dot{\mathbf{q}}) = -m_2 l_1 l_{c2}\sin q_2 \begin{bmatrix} \dot{q}_2 & \dot{q}_1 + \dot{q}_2 \\ \dot{q}_1 & 0 \end{bmatrix}$$

Two-Link Space Robot

- ## Flexible Joint Dynamics
  - Derived by including the **kinetic energy of the rotors** and considering the **elastic potential energy of the linear springs** at the joints



$$\mathbf{M}_r(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{C}_r(\mathbf{q},\dot{\mathbf{q}})\dot{\mathbf{q}} = \mathbf{k}(\mathbf{q}_m - \mathbf{q})$$

$$\mathbf{J}_m\mathbf{q}_m + \mathbf{k}(\mathbf{q}_m - \mathbf{q}) = \boldsymbol{\tau}$$

•The link dynamics and the motor dynamics Eqs. are only coupled by the elastic torque term $\mathbf{k}(\mathbf{q}_m - \mathbf{q})$

Flexible Joint Control Survey

- **Flexible Joint Control Categories**
  - Proportional Derivative (Tomei, 1991)
  - Singular Perturbation-Based (Spong, 1989)
  - Integral Manifold (Ghorbel and Spong, 1992)
  - Feedback Linearization (De Luca, 1998, 2005, 2008)
  - Optimal (Merabet and Gu, 2008)
  - Adaptive (Slotine, 1987, 1988, 2008)
  - Simple Adaptive Control (Sasiadek, Ulrich, Barkana, 2009, 2010, 2011, 2012)
  - Robust (Lee, Yeon, Park and Yim, 2006, 2007)
  - Nonlinear Backstepping (Brogliato, 1995, 1998)
  - Fuzzy and Neural Network (Zeman, 1989, 1997)
  - Iterative (Wang, 1995)

Flexible Joint Control Survey

- **Unresolved Issues**
  - Simple and efficient algorithms considering practical limitations are yet to be developed
  - Applicability of existing control strategies to real-time space applications (no gravity, highly limited computational load) needs to be assessed
  - Performance validation should be done with large square trajectories (flexible effects are more noticeable → greater control challenge)
-

Advanced Control Strategies

- **Compare 4 control strategies for flexible joint space robots**
    - Slotine and Li controller
    - PD controller
    - Singular Perturbation-Based controller
    - Nonlinear Backstepping controller

- **Compare their respective performance while tracking a 12.6 m x 12.6 m square trajectory**

Advanced Control Strategies

- ***Slotine and Li*** **Control Strategy**

Slotine J. J. E. and Li W., "On the Adaptive Control of Robot Manipulators," *International Journal of Robotics Research*, Vol. 6, No. 3, pp. 49-59, 1987.

$$\boldsymbol{\tau}_r = \mathbf{M}_r(\mathbf{q})\ddot{\mathbf{q}}_r + \mathbf{C}_r(\mathbf{q},\dot{\mathbf{q}})\dot{\mathbf{q}}_r - \mathbf{K}_d\mathbf{s}$$

where

$$\dot{\mathbf{q}}_r = \dot{\mathbf{q}}_c + \boldsymbol{\Lambda}(\mathbf{q}_c - \mathbf{q})$$

$$\ddot{\mathbf{q}}_r = \ddot{\mathbf{q}}_c + \boldsymbol{\Lambda}(\dot{\mathbf{q}}_c - \dot{\mathbf{q}})$$

$$\mathbf{s} = -(\dot{\mathbf{q}}_c - \dot{\mathbf{q}}) - \boldsymbol{\Lambda}(\mathbf{q}_c - \mathbf{q}) = \dot{\mathbf{q}} - \dot{\mathbf{q}}_r$$

$\mathbf{K}_d =$ positive constant gain matrix

Advanced Control Strategies

- **PD Control Strategy**

  Tomei P., “A Simple PD Controller for Robots with Elastic Joints,” *IEEE Transactions on Automatic Control*, Vol. 36, No. 10, pp. 1208-1213, 1991.

$$\boldsymbol{\tau} = \mathbf{K}_p(\mathbf{q}_{mc} - \mathbf{q}_m) - \mathbf{K}_d\dot{\mathbf{q}}_m$$

where

$$\mathbf{q}_{mc} = \mathbf{q}_c$$

$\mathbf{K}_p =$ positive constant gain matrix

$\mathbf{K}_d =$ positive constant gain matrix

Advanced Control Strategies

- **Singular Perturbation-Based Control Strategy**

  Spong M. W., "Adaptive Control of Flexible Joint Manipulators," *Systems and Control Letters*, Vol. 13, pp. 15-21, 1989.

where

$$\boldsymbol{\tau} = \boldsymbol{\tau}_s + \boldsymbol{\tau}_f$$

where

$\boldsymbol{\tau}_s = \boldsymbol{\tau}_r =$ SLI control algorithm for space robots defined earlier

$$\boldsymbol{\tau}_f = \mathbf{K}_v(\dot{\mathbf{q}} - \dot{\mathbf{q}}_m)$$

$\mathbf{K}_v =$ positive constant gain matrix

Advanced Control Strategies

- ## Nonlinear Backstepping Control Strategy

Brogliato B., Ortega R. and Lozano R., “Global Tracking Controllers for Flexible Joint Manipulators: A Comparative Study,” *Automatica*, Vol. 31, No. 7, pp. 941-956, 1995

$$\boldsymbol{\tau} = \mathbf{J}_m\left[\ddot{\mathbf{q}}_{mc} - 2(\dot{\mathbf{q}}_m - \dot{\mathbf{q}}_{mc}) - 2(\mathbf{q}_m - \mathbf{q}_{mc}) - (\dot{\mathbf{s}} + \mathbf{s})\right] + \mathbf{k}(\mathbf{q}_m - \mathbf{q})$$

where

$$\mathbf{q}_{mc} = \mathbf{k}^{-1}\boldsymbol{\tau}_r + \mathbf{q}$$

$$\dot{\mathbf{q}}_{mc} = \mathbf{k}^{-1}\dot{\boldsymbol{\tau}}_r + \dot{\mathbf{q}}$$

$$\ddot{\mathbf{q}}_{mc} = \mathbf{k}^{-1}\boxed{\ddot{\boldsymbol{\tau}}_r} + \boxed{\ddot{\mathbf{q}}}$$

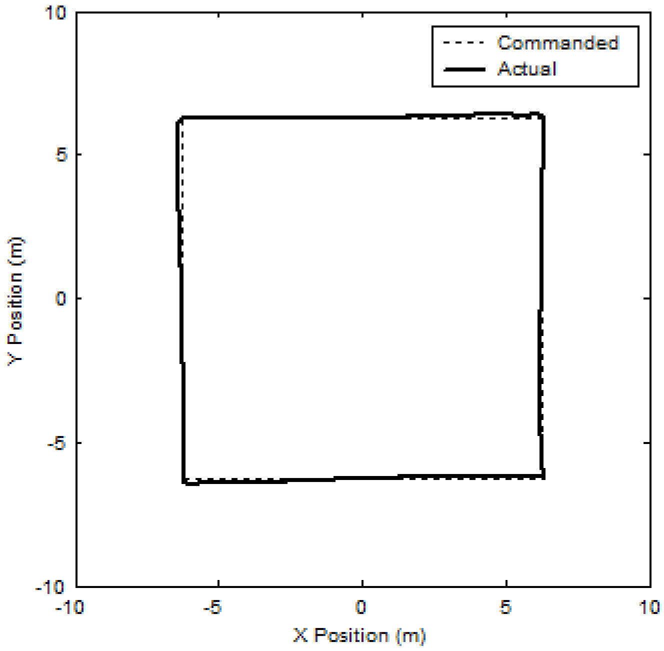
$$\dot{\mathbf{s}} = -(\ddot{\mathbf{q}}_c - \boxed{\ddot{\mathbf{q}}}) - \boldsymbol{\Lambda}(\dot{\mathbf{q}}_c - \dot{\mathbf{q}}) = \boxed{\ddot{\mathbf{q}}} - \ddot{\mathbf{q}}_r$$

$\mathbf{k}$ = joint stiffness matrix

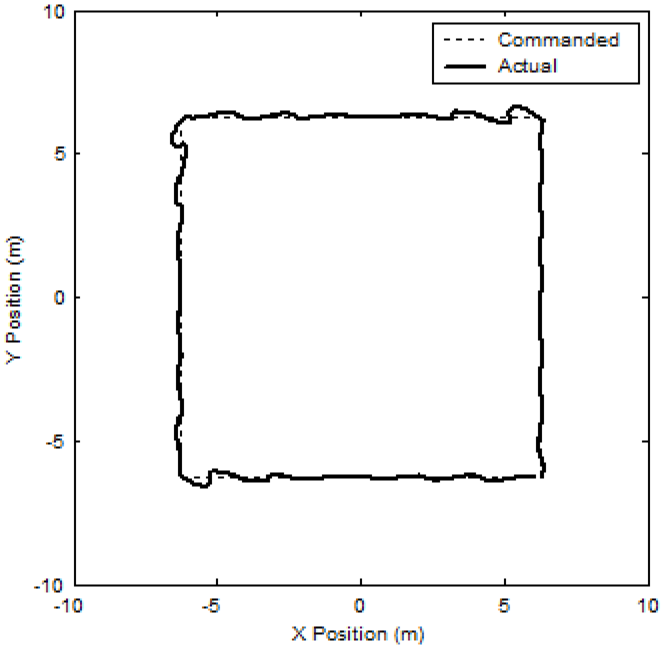
Note: The joint **acceleration** can be obtained by inverting the link dynamics equation and the **jerk** is obtained by time-differentiating the acceleration

Advanced Control Strategies

- **Simulation Results**

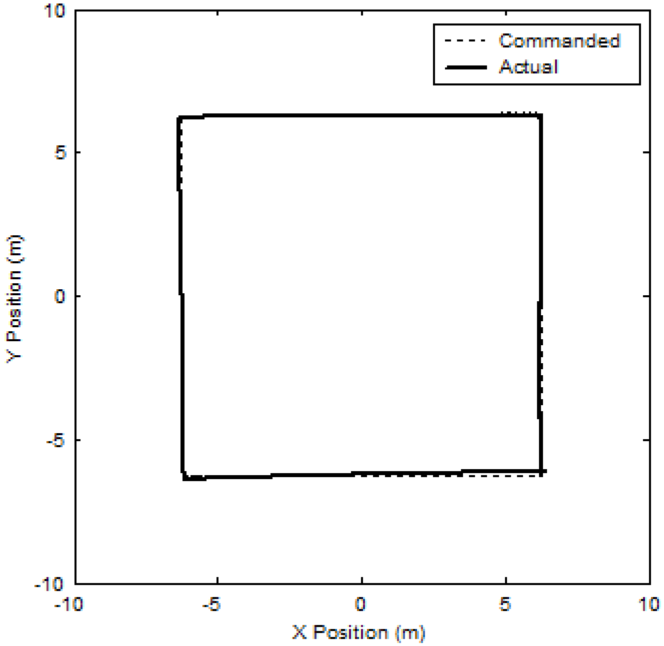


Slotine and Li

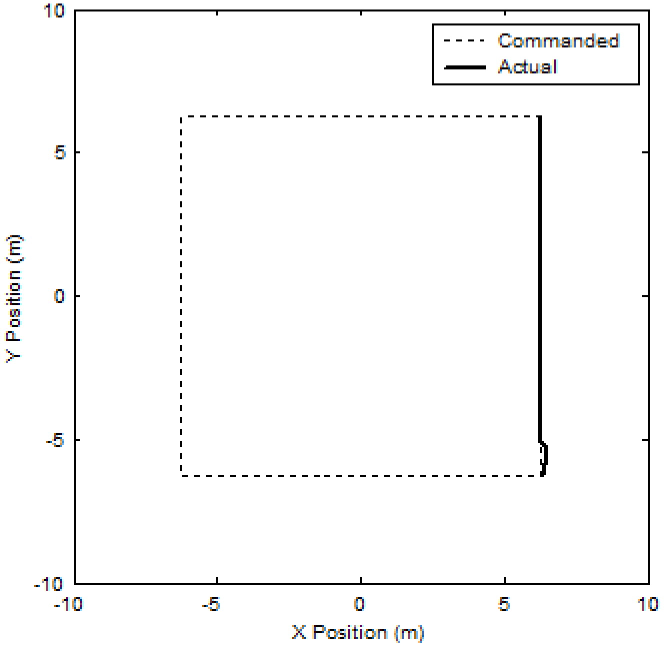


PD

Advanced Control Strategies



Singular Perturbation-Based



Nonlinear Backstepping

Novel Adaptive Control Scheme

- **Further Improvement**
  - The **Singular Perturbation-Based** strategy must be extended for robots with unknown/variable joint stiffness coefficients
  - The idea is to replace the rigid term (SLI) with an adaptive control algorithm

$$\boldsymbol{\tau} = \boxed{\boldsymbol{\tau}_s} + \boldsymbol{\tau}_f$$

  - As a first step, a novel model reference adaptive control (MRAC) scheme for rigid joint space robots is presented

Novel Adaptive Control Scheme

- **Adaptive Jacobian Scheme**

$$\boldsymbol{\tau} = \mathbf{J}(\mathbf{q})^T \left\{ \mathbf{K}_p(t) \begin{bmatrix} e_x \\ e_y \end{bmatrix} + \mathbf{K}_d(t) \begin{bmatrix} \dot{e}_x \\ \dot{e}_y \end{bmatrix} \right\}$$

where

$\mathbf{J}(\mathbf{q}) =$ Jacobian matrix

$$\begin{bmatrix} e_x & e_y \end{bmatrix}^T = \left[\left(x_{ref} - x \right) \quad \left(y_{ref} - y \right) \right]^T \qquad x = l_1 \cos q_1 + l_2 \cos(q_1 + q_2)$$

$$\begin{bmatrix} \dot{e}_x & \dot{e}_y \end{bmatrix}^T = \left[\left(\dot{x}_{ref} - \dot{x} \right) \quad \left(\dot{y}_{ref} - \dot{y} \right) \right]^T \qquad y = l_1 \sin q_1 + l_2 \sin(q_1 + q_2)$$

$$\frac{x_{ref}}{x_c} = \frac{y_{ref}}{y_c} = \frac{\omega_n^{\ 2}}{s^2 + 2\zeta\omega_n s + \omega_n^{\ 2}}$$

Novel Adaptive Control Scheme

where the proportional adaptive gain is adapted as

$$\mathbf{K}_{p}(t) = \mathbf{K}_{pp}(t) + \int \dot{\mathbf{K}}_{pi}(t)dt$$

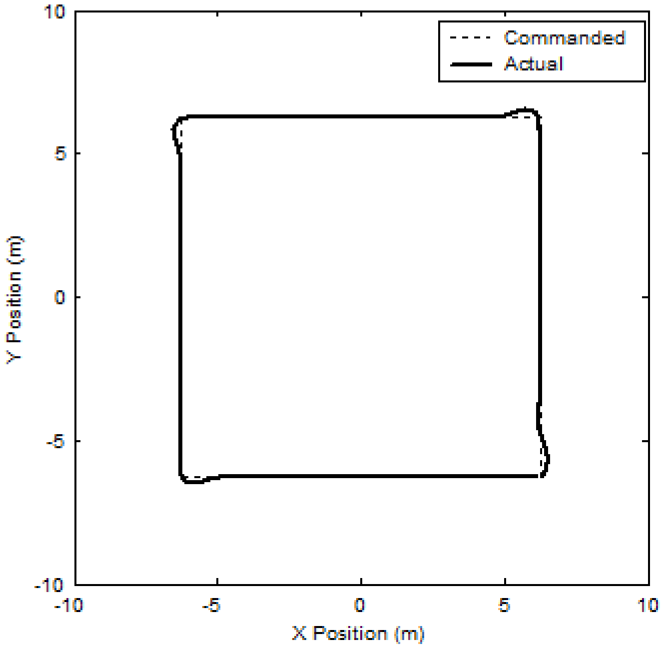
with

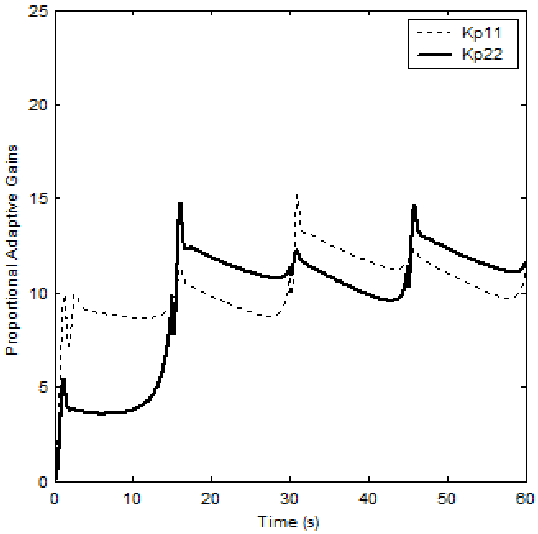
$$\mathbf{K}_{pp}(t) = \begin{bmatrix} e_x{}^2 \Gamma_{pp} & 0 \\ 0 & e_y{}^2 \Gamma_{pp} \end{bmatrix}$$

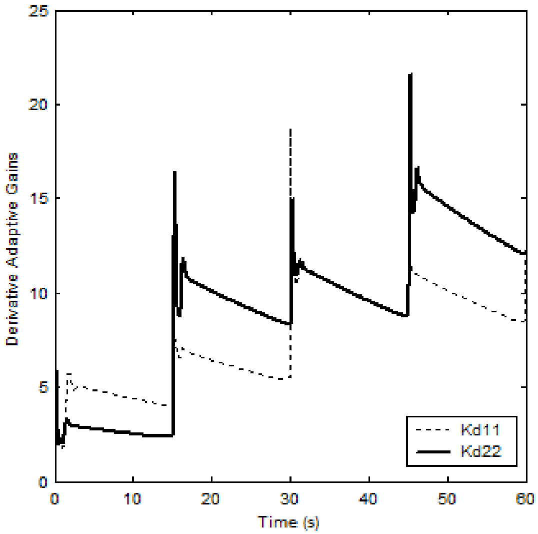
$$\dot{\mathbf{K}}_{pi}(t) = \begin{bmatrix} e_x{}^2 \Gamma_{pi} - \delta_p K_{pi11}(t) & 0 \\ 0 & e_y{}^2 \Gamma_{pi} - \delta_p K_{pi22}(t) \end{bmatrix}$$

Novel Adaptive Control Scheme

- **Simulation Results**



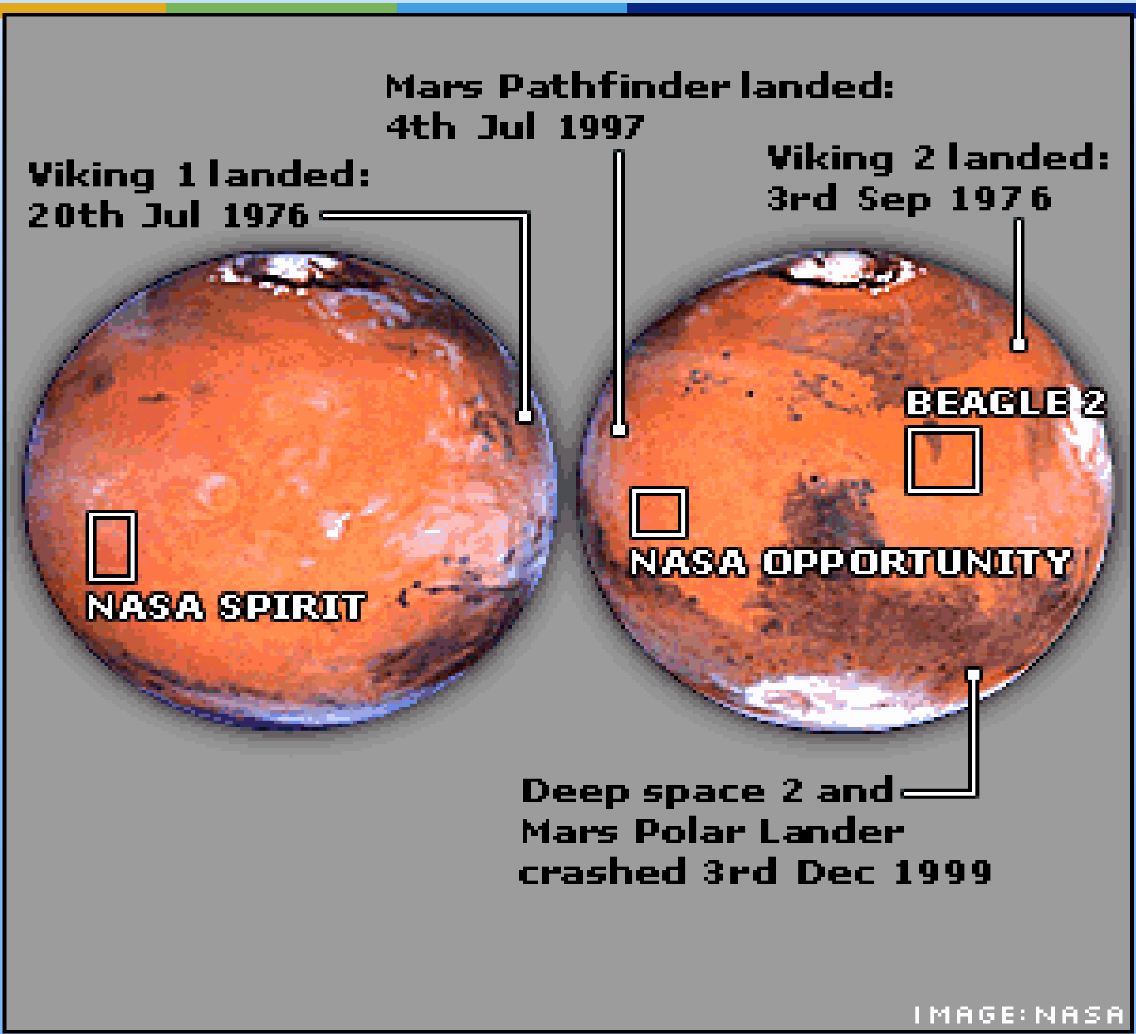




Space Robotic Missions to Mars

- Viking Lander Missions
- Pathfinder/Sojourner Mission (Pathfinder landed July 4-th, 1997)
- Spirit / Opportunity Mission
- Curiosity Mission (will land on August 6, 2012)

Mars robotic missions



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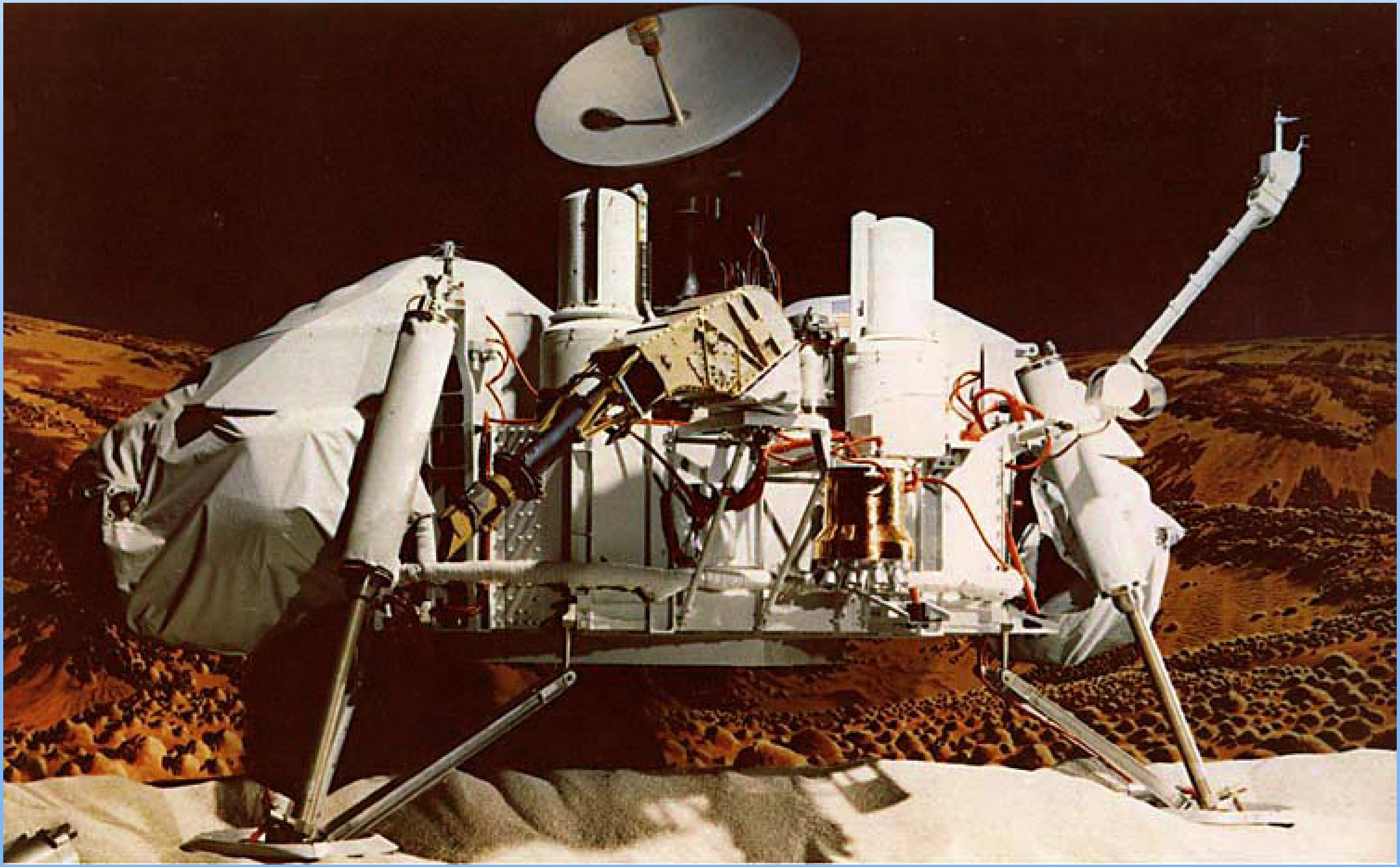
Viking Lander Missions (Orbiter 1 and Orbiter 2)



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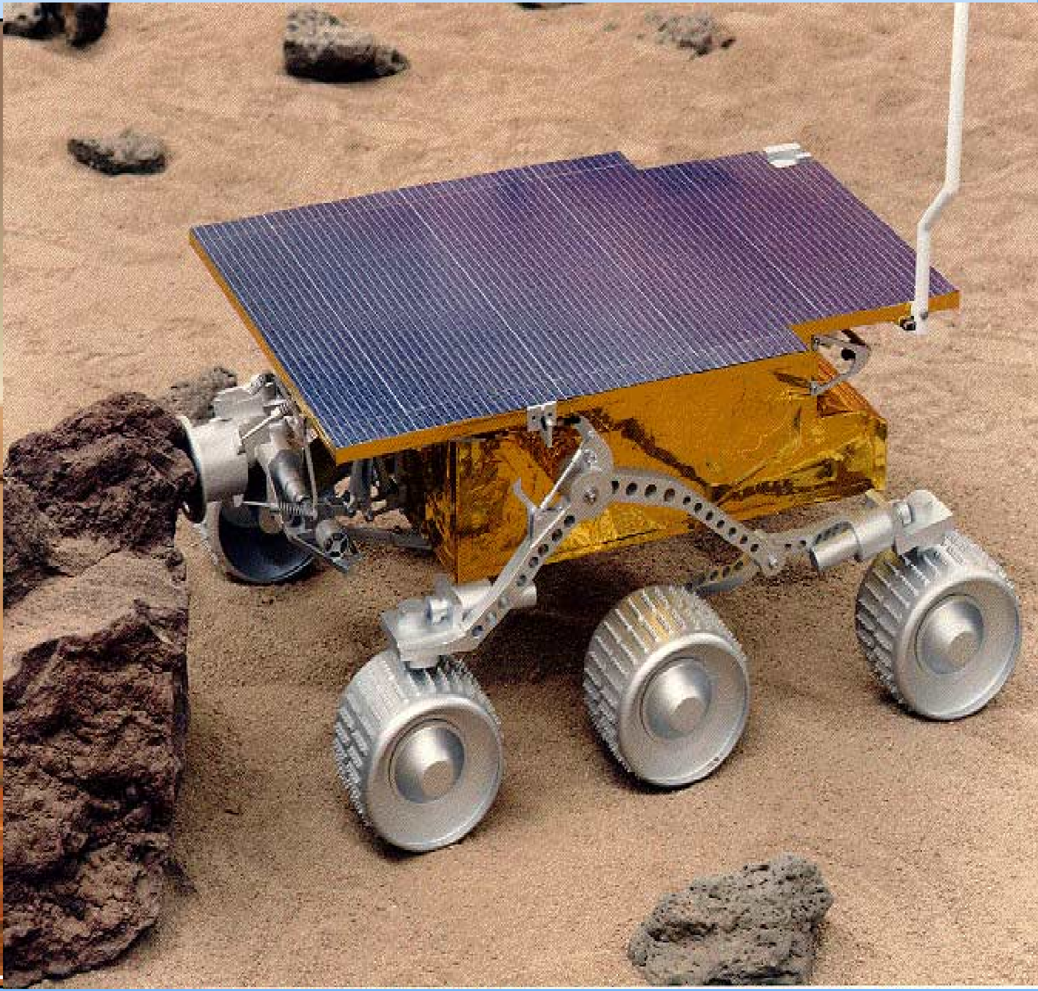
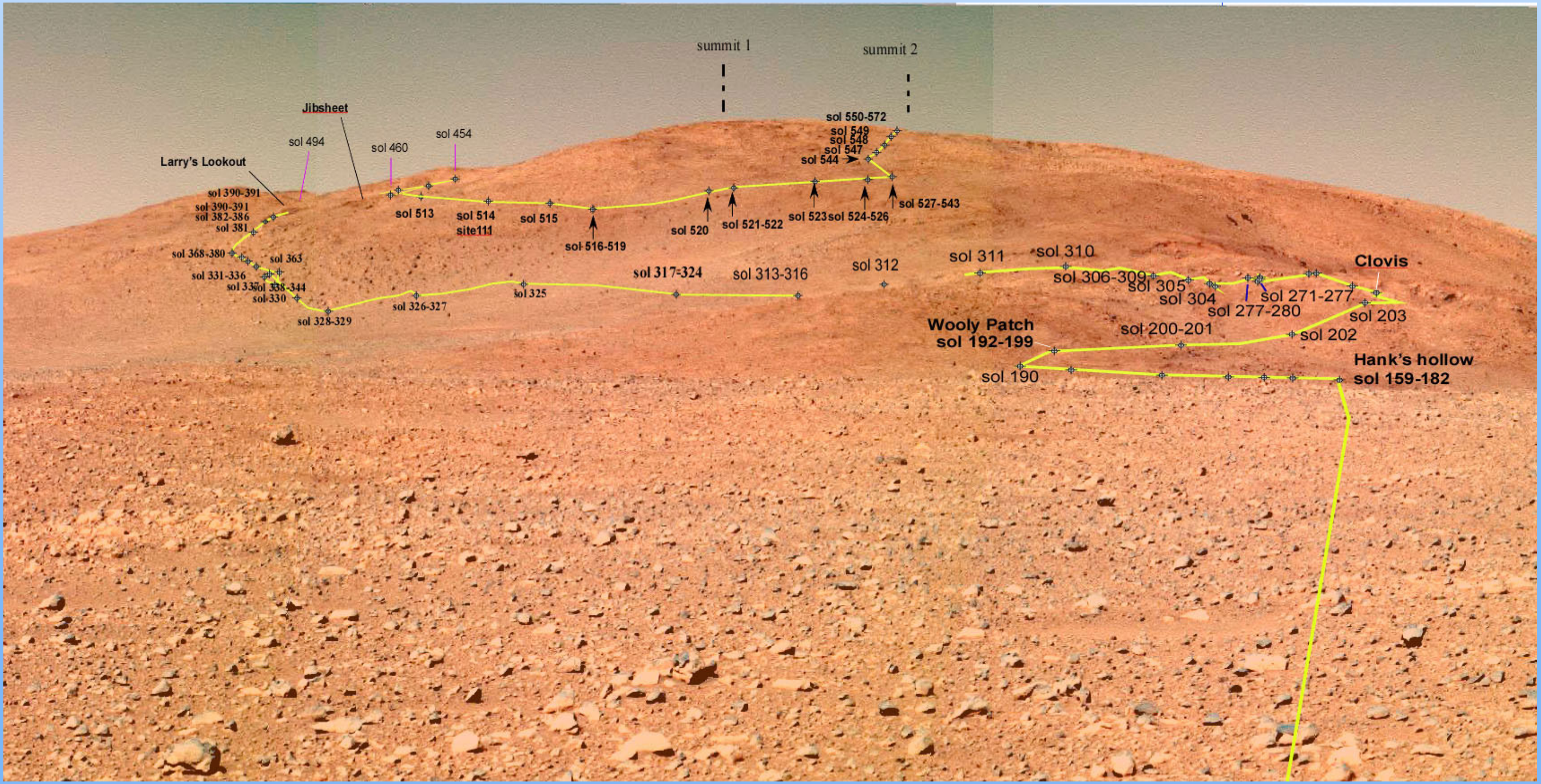
Phoenix Lander

“Spirit”/’Opportunity” and “Pathfinder”/ “Sojourner” Rovers



NASA "Spirit" Rover itinerary



NASA Mars Rover Opportunity Mission image taken between Dec. 21, 2011, and May 8, 2012

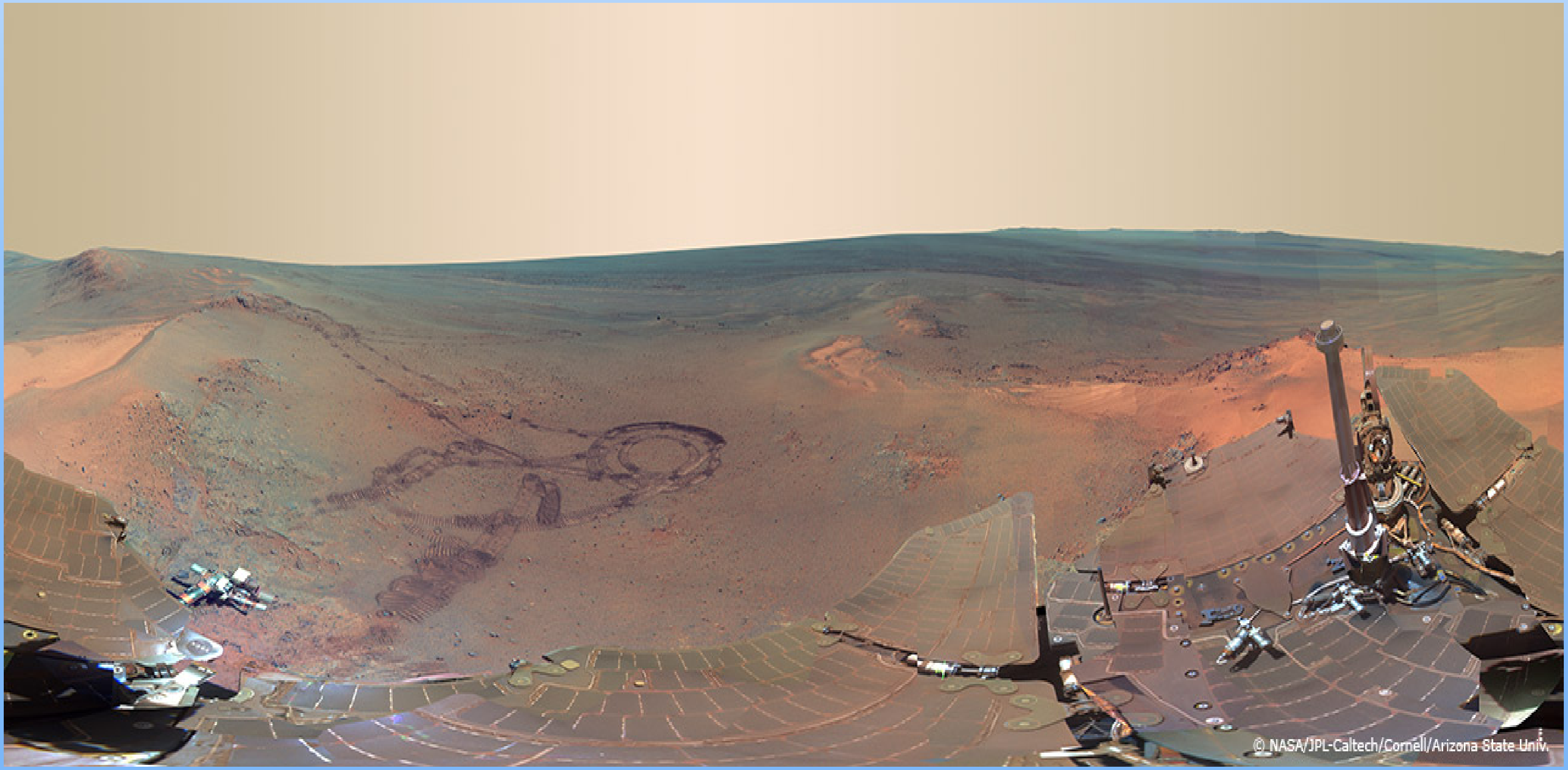


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Image taken by NASA "Opportunity" robot

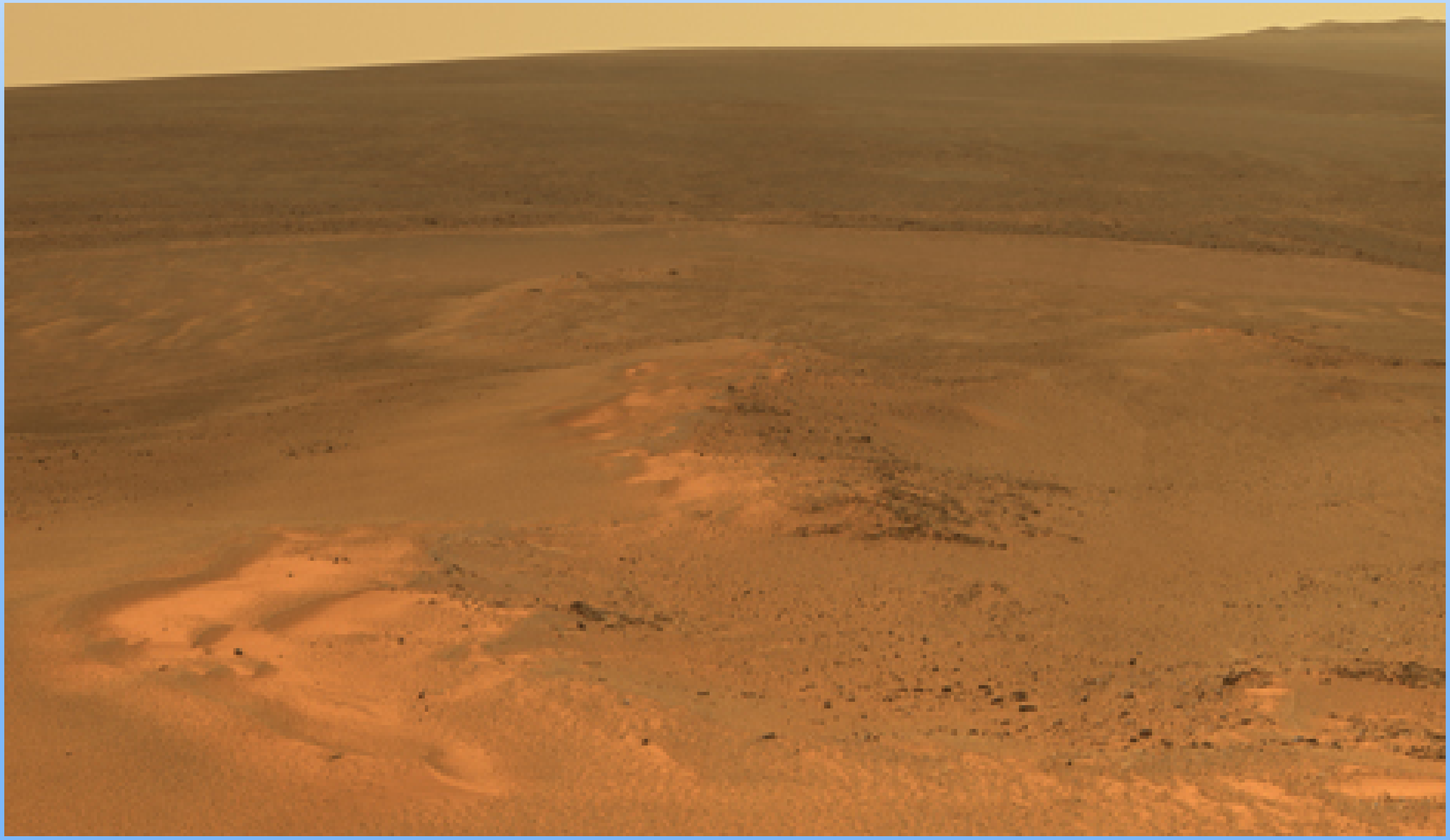

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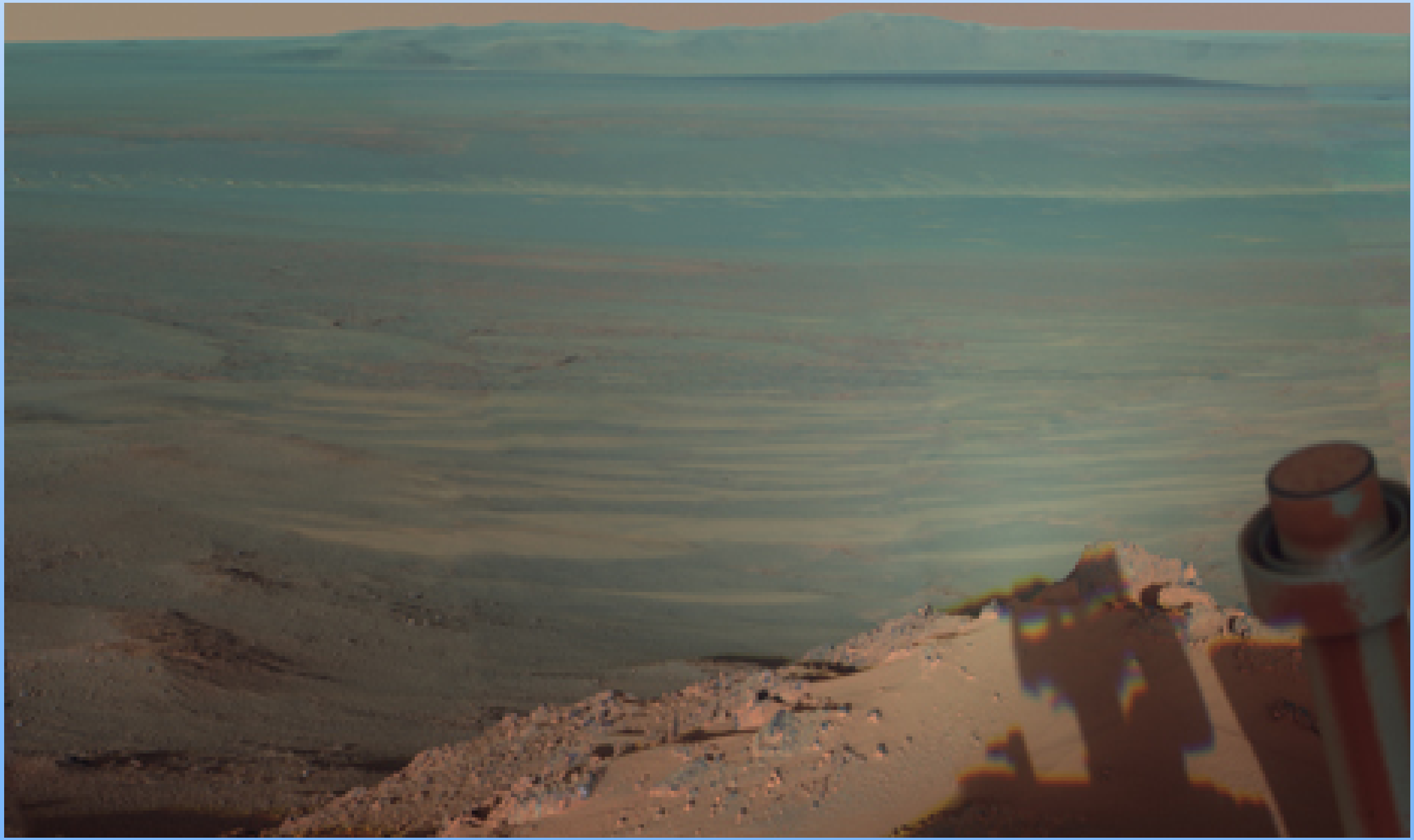
Image taken by “Opportunity” robot



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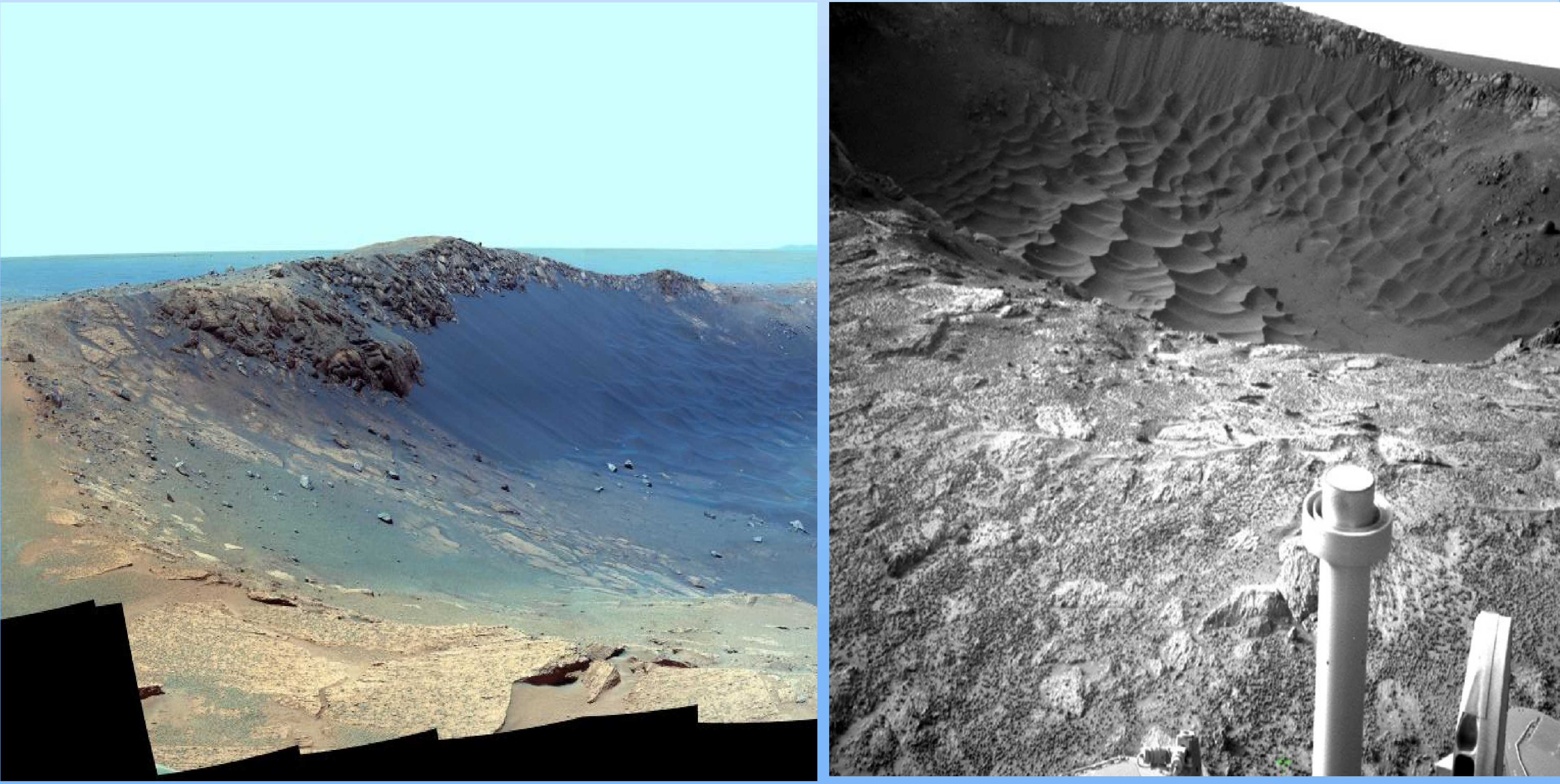
Images taken by Opportunity robot



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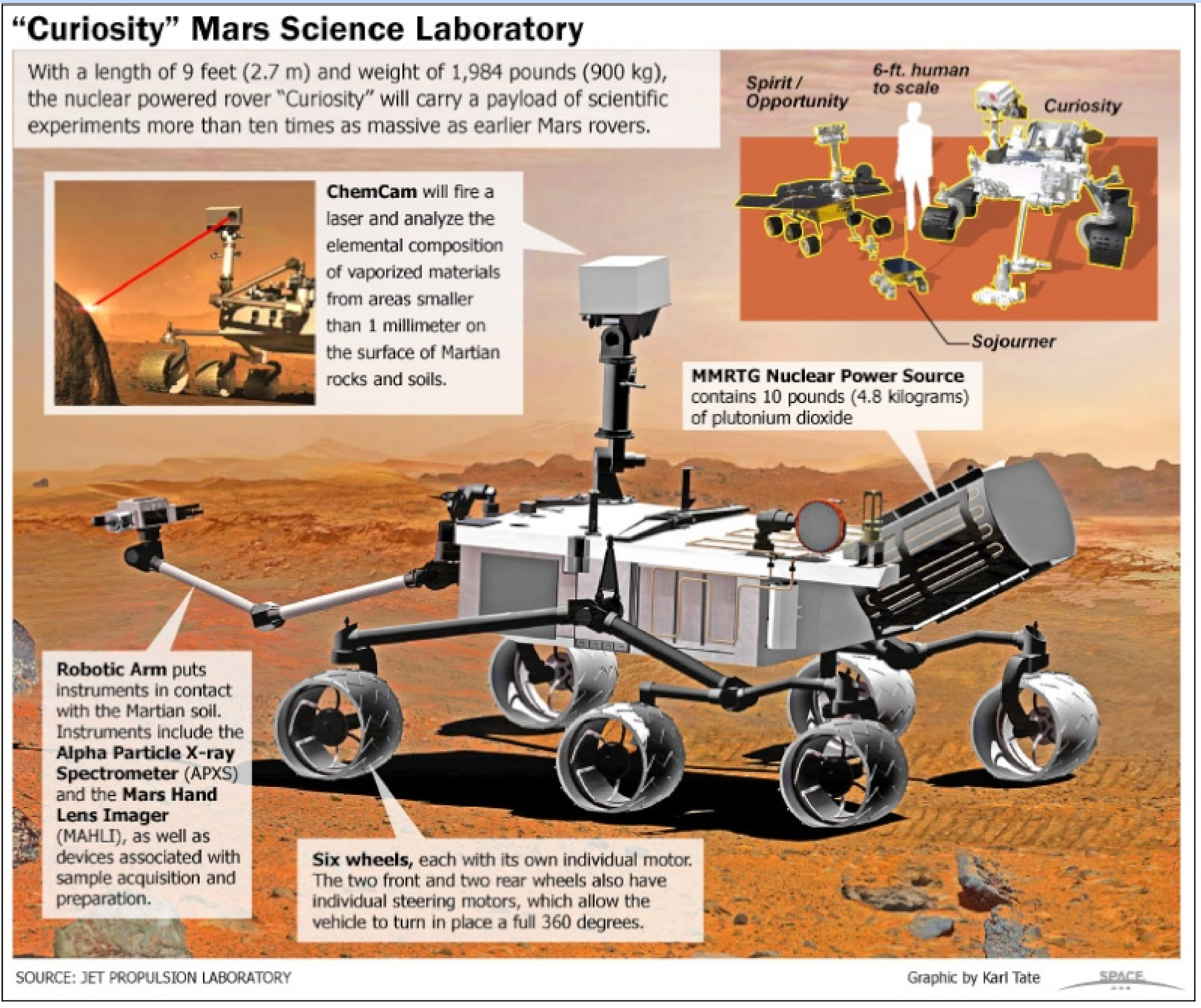
Space Robots (Phoenix lander and Curiosity mobile robot)



“Curiosity” Mars Science Laboratory

With a length of 9 feet (2.7 m) and weight of 1,984 pounds (900 kg), the nuclear powered rover “Curiosity” will carry a payload of scientific experiments more than ten times as massive as earlier Mars rovers.

ChemCam will fire a laser and analyze the elemental composition of vaporized materials from areas smaller than 1 millimeter on the surface of Martian rocks and soils.

MMRTG Nuclear Power Source contains 10 pounds (4.8 kilograms) of plutonium dioxide

Robotic Arm puts instruments in contact with the Martian soil. Instruments include the **Alpha Particle X-ray Spectrometer** (APXS) and the **Mars Hand Lens Imager** (MAHLI), as well as devices associated with sample acquisition and preparation.

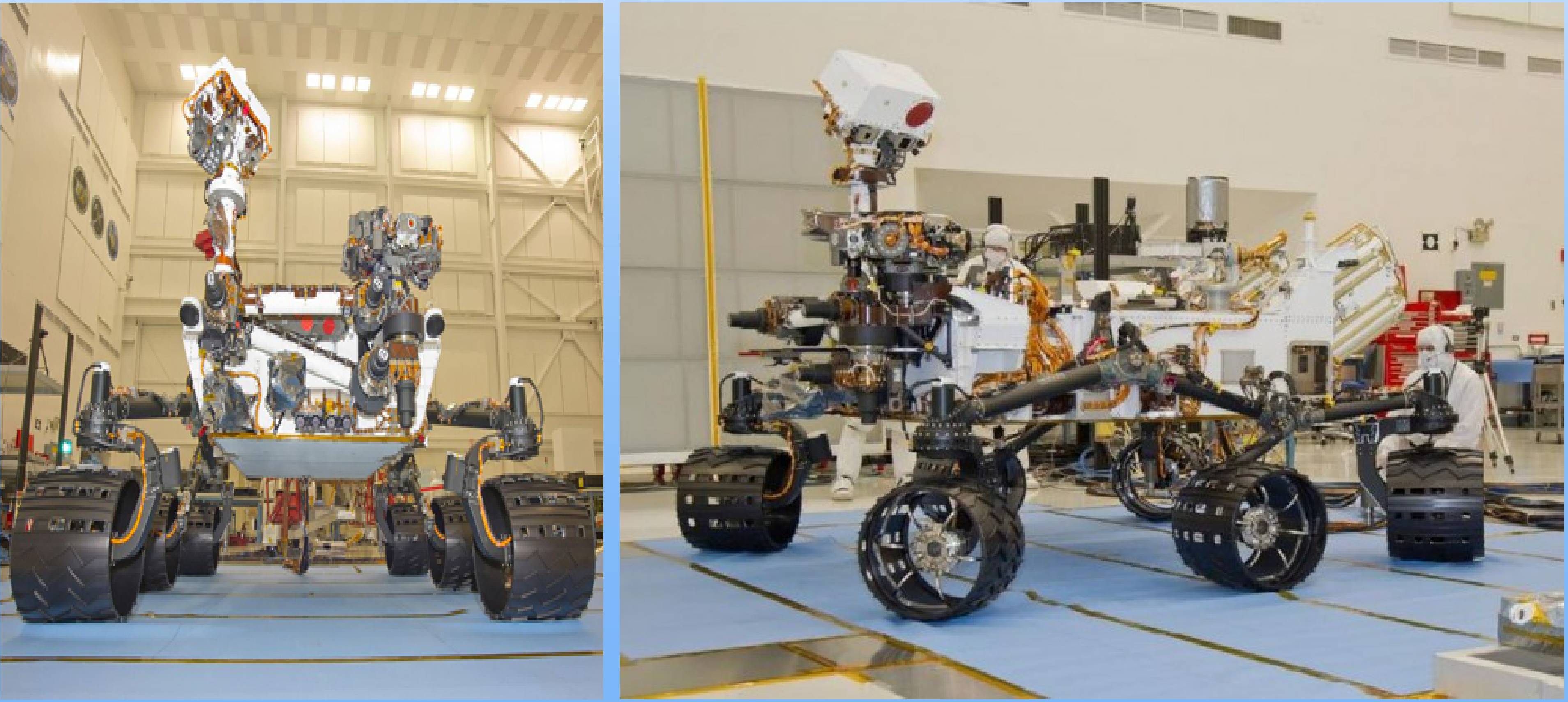
Six wheels, each with its own individual motor. The two front and two rear wheels also have individual steering motors, which allow the vehicle to turn in place a full 360 degrees.

SOURCE: JET PROPULSION LABORATORY

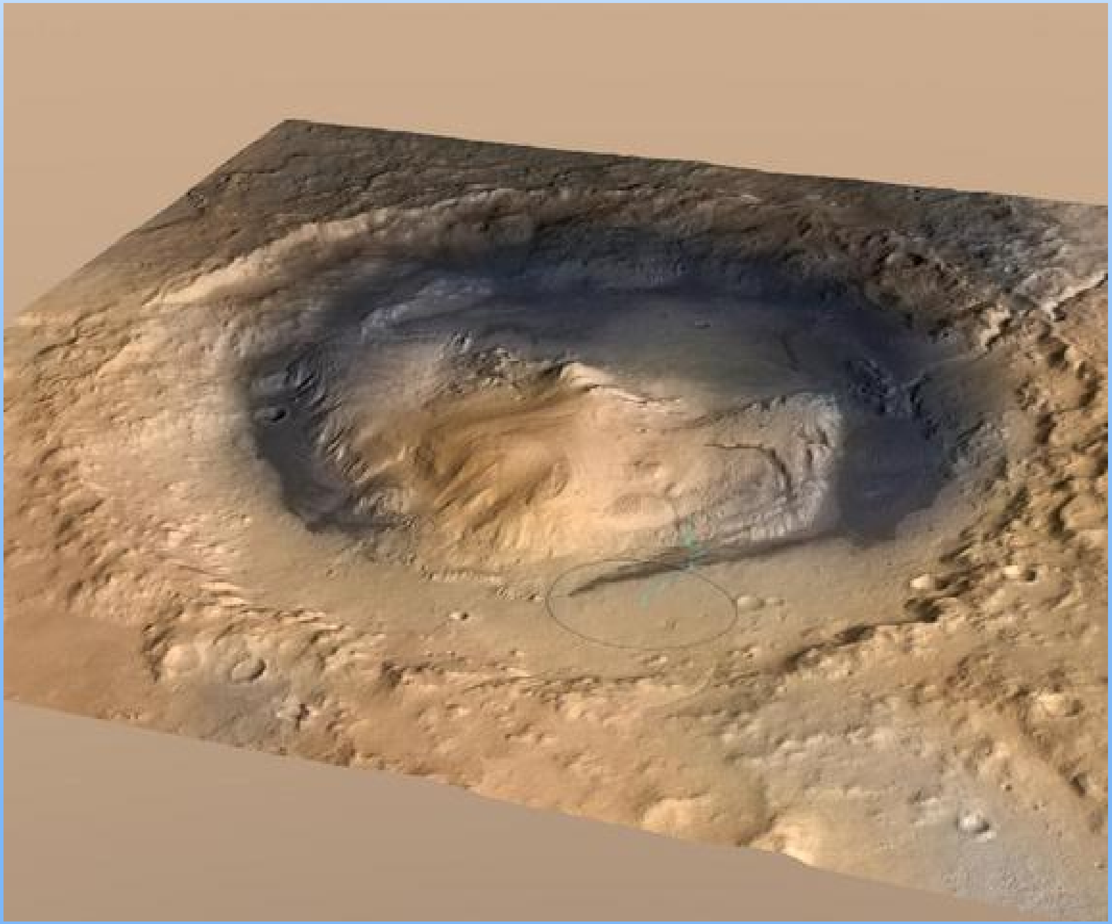
Graphic by Karl Tate

www.nasa.gov

"Curiosity" Mars Rover



Curiosity landing site

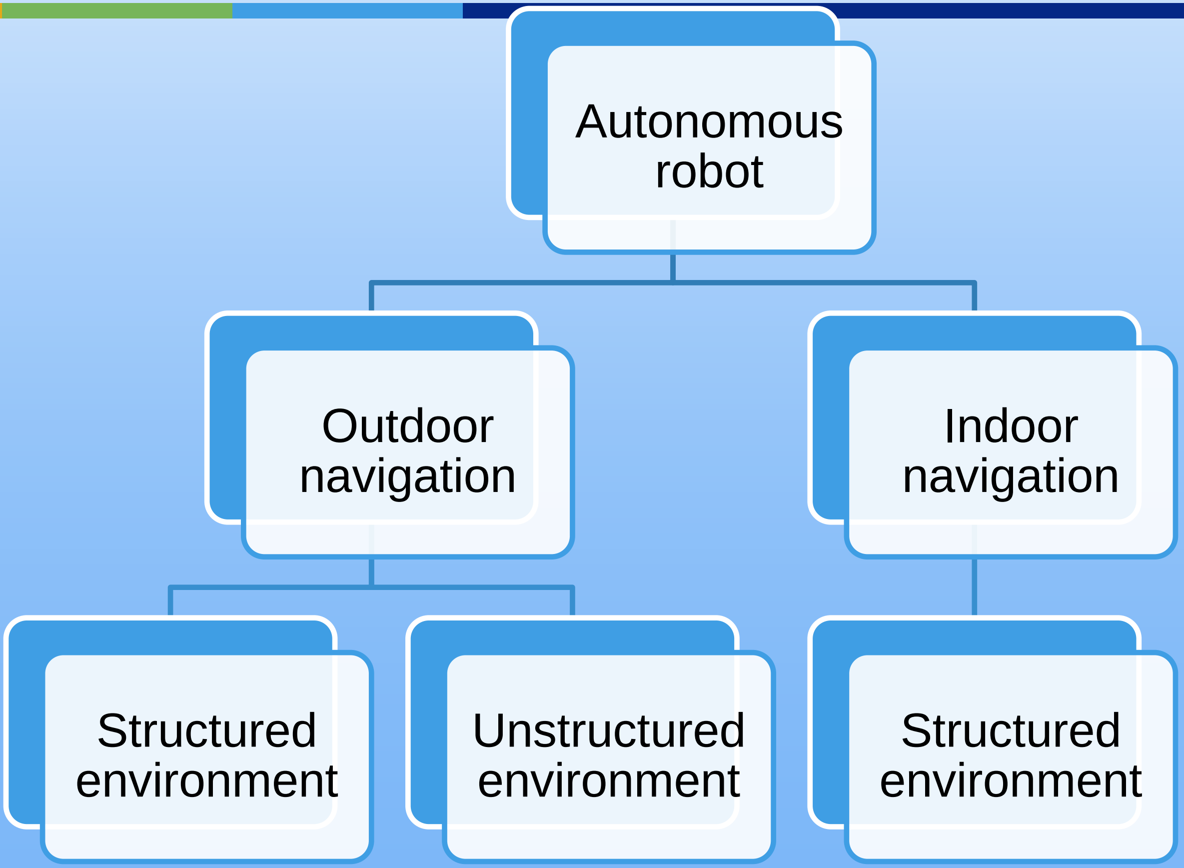


Mobile space robots design 2

“Curiosity”, “Spirit” and “Sojourner”

www.nasa.gov

Guidance, Navigation and Control


Autonomous robot

Outdoor navigation

Indoor navigation

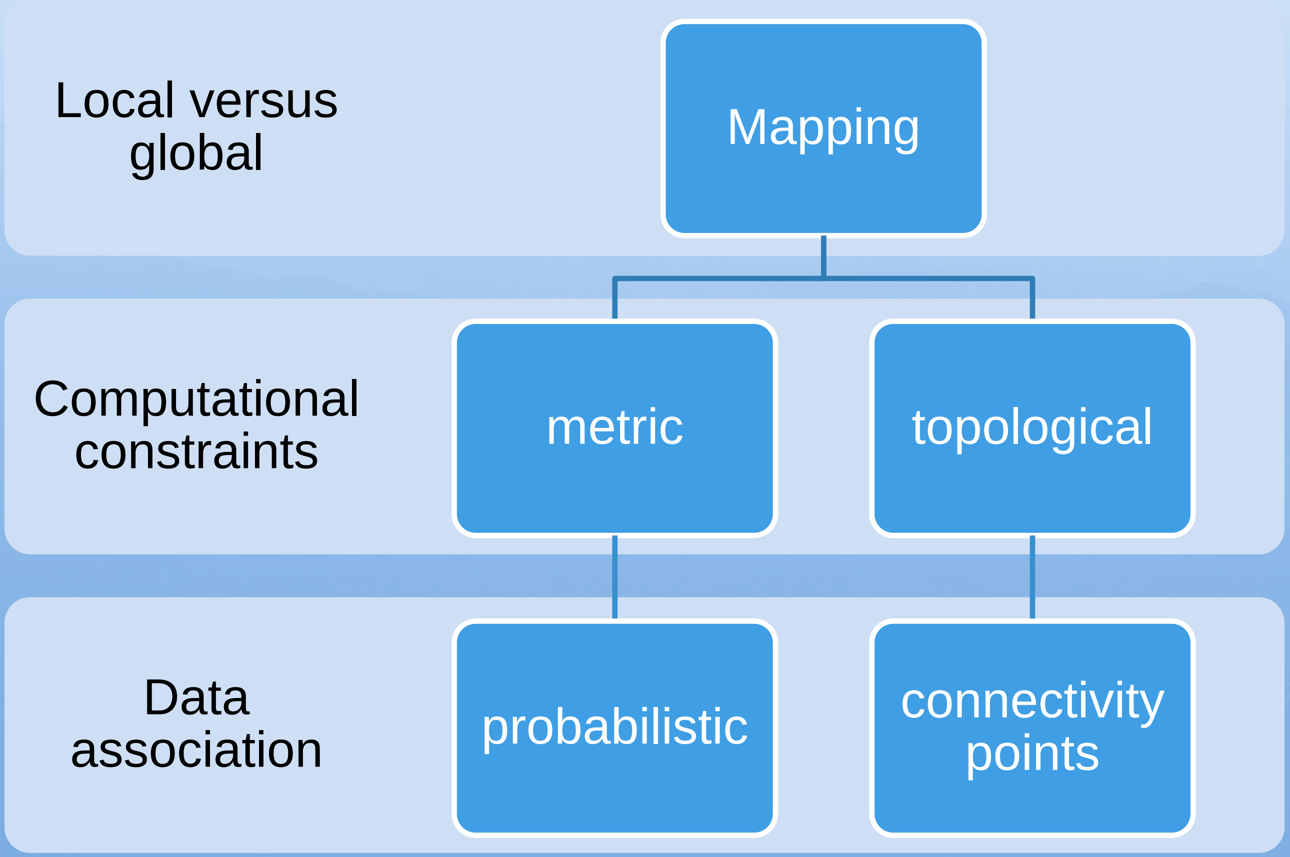
Structured environment

Unstructured environment

Structured environment

- Mapping
  - static
  - dynamic

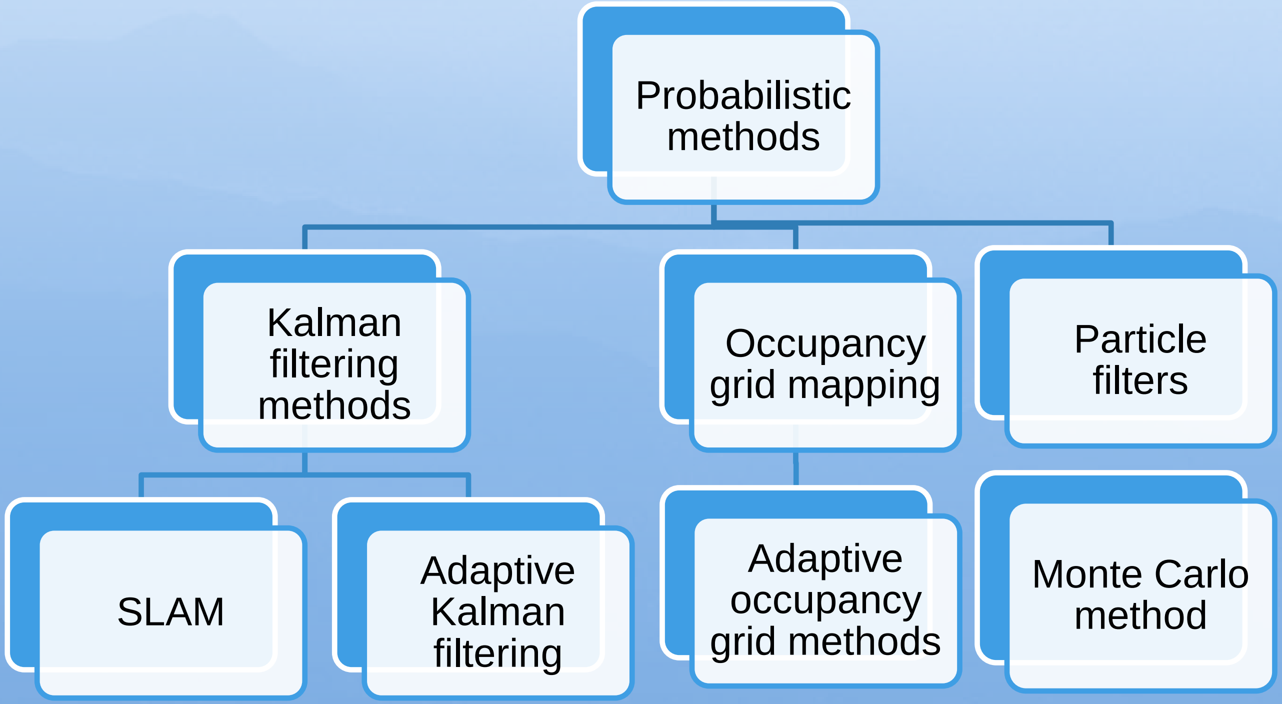
- Mapping
  - local
  - global



Local versus global

Computational constraints

Data association



Probabilistic methods

Kalman filtering methods

Occupancy grid mapping

Particle filters

SLAM

Adaptive Kalman filtering

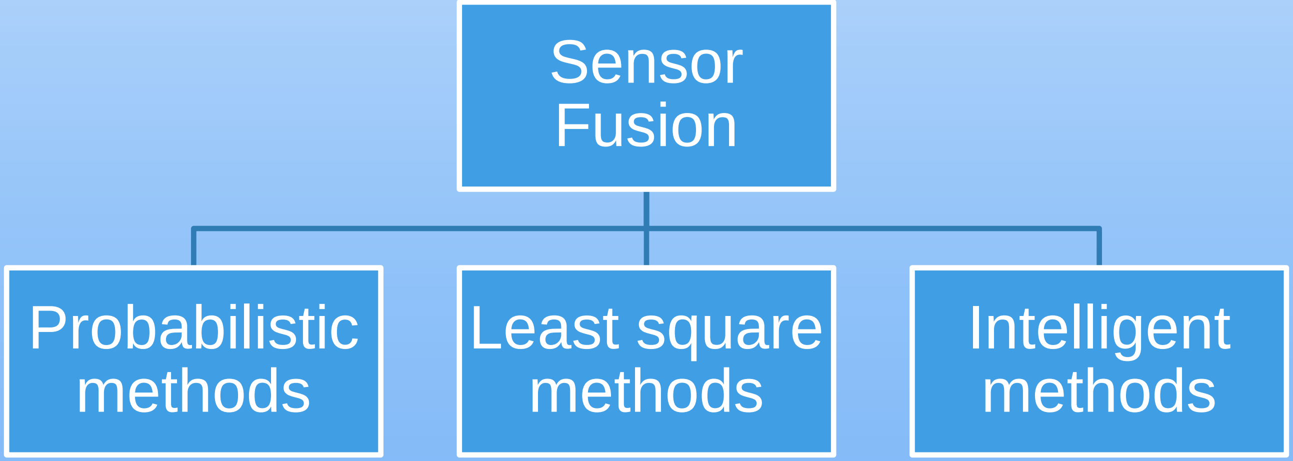
Adaptive occupancy grid methods

Monte Carlo method

Sensor/Data Fusion

- Sensor fusion is a measurement integration procedure
- Sensor fusion is one of the most important elements of robot GNC system

Sensor Fusion



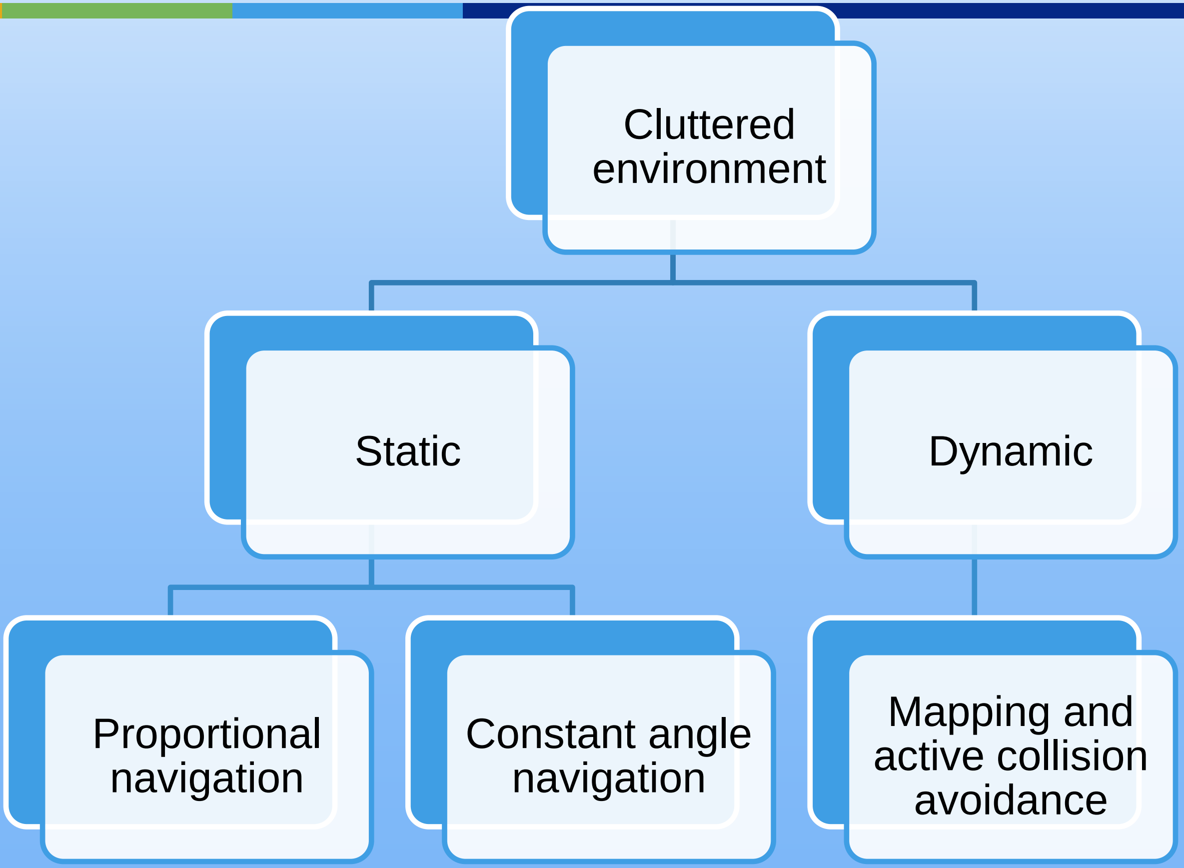
Sensor Fusion

Probabilistic methods

Least square methods

Intelligent methods

Collision avoidance



Cluttered environment

Static

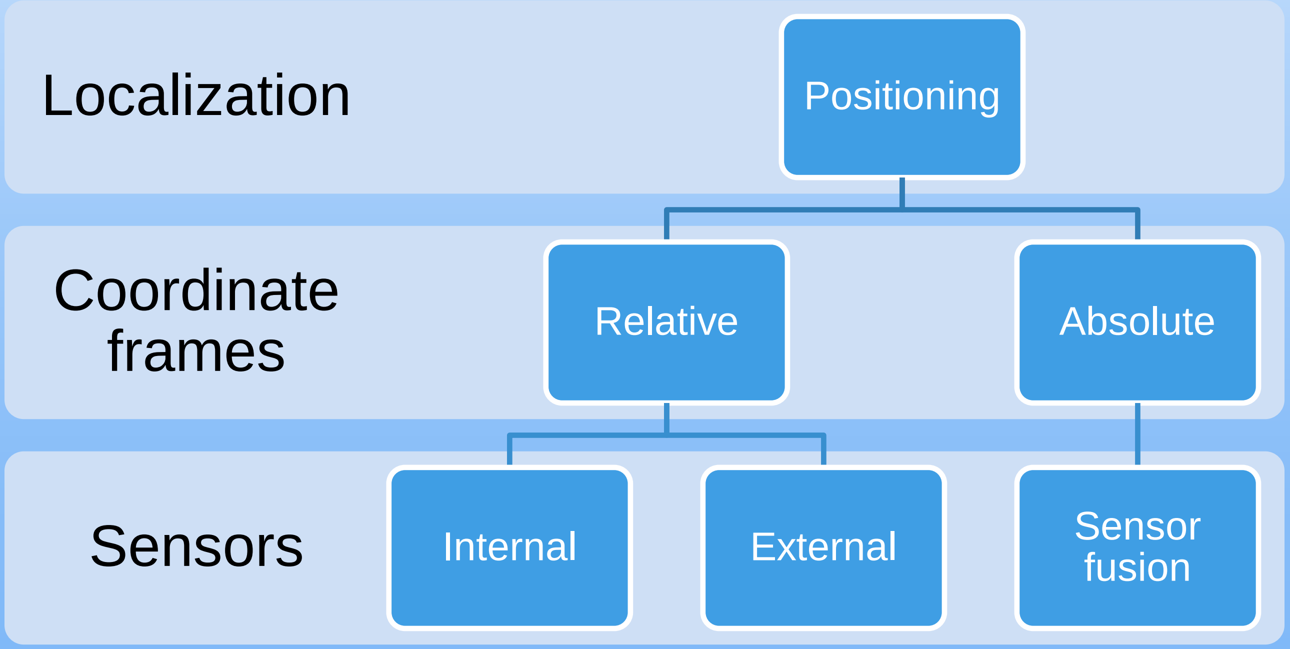
Dynamic

Proportional navigation

Constant angle navigation

Mapping and active collision avoidance

Trajectory Tracking



Localization

Positioning

Coordinate frames

Relative

Absolute

Sensors

Internal

External

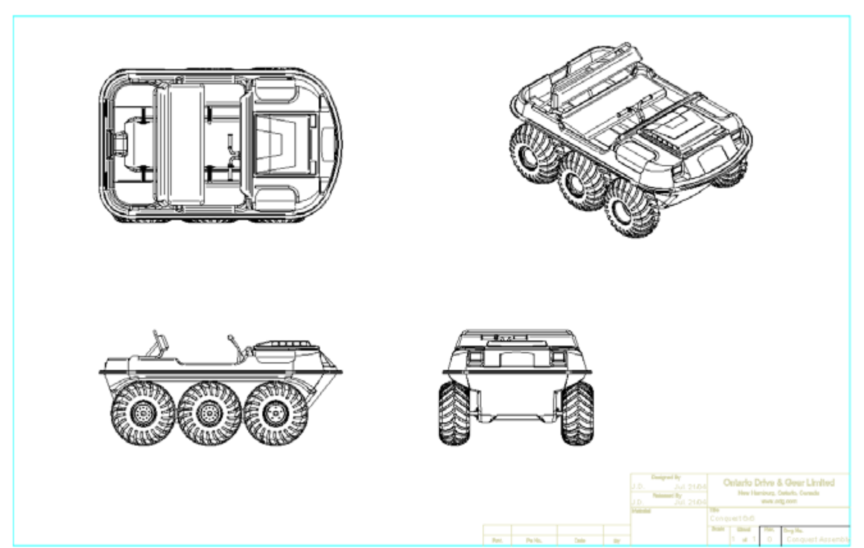
Sensor fusion

Mobile robot navigation through two identifiable points

- Gate passage problem
- Navigation with vision system

ARGO 6x6 Conquest

(Ontario Drive & Gear Limited Inc)

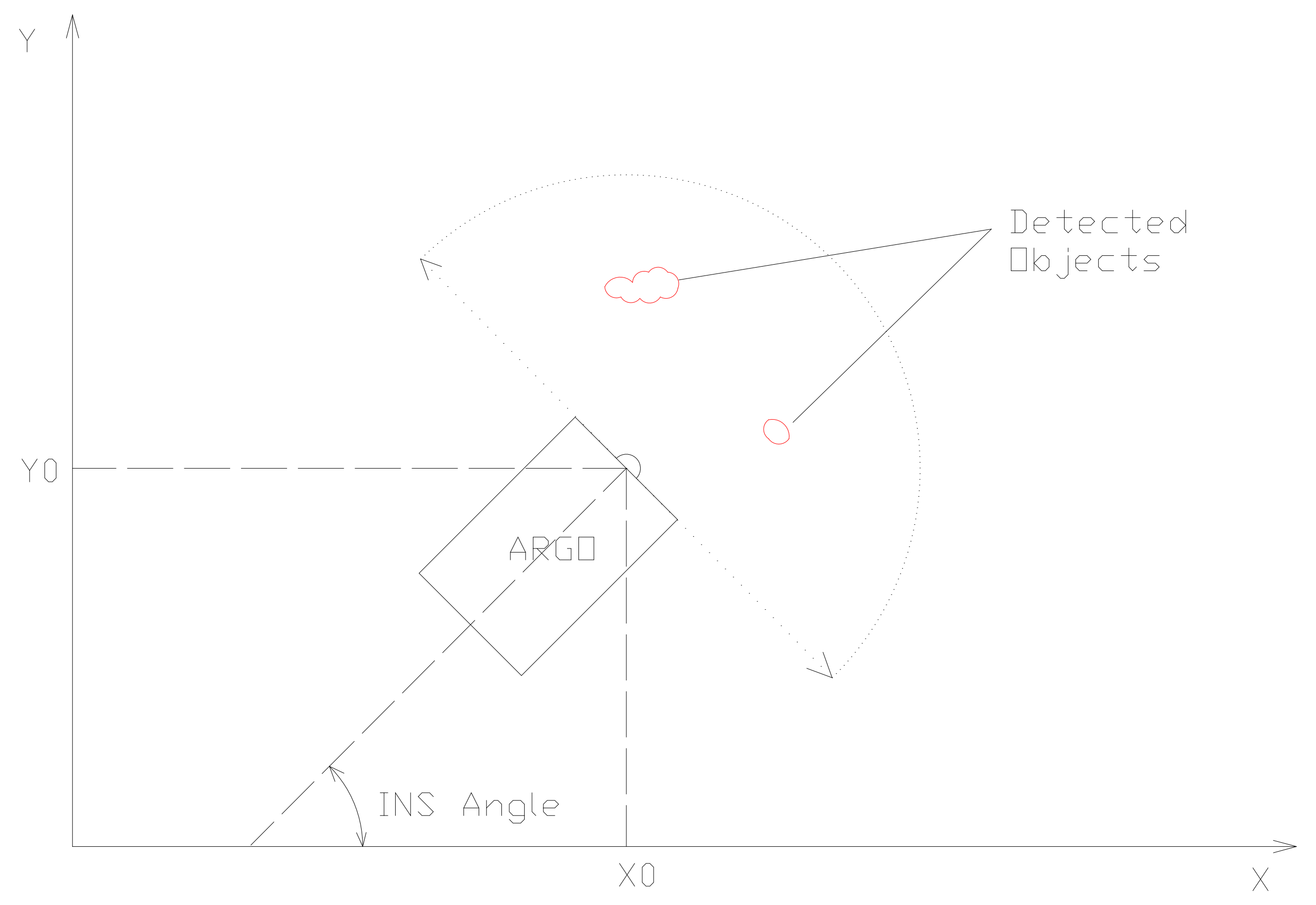


✓ 6 wheel drive
✓ 4 cycle engine with 200 HP
✓ 617 cc and load capacity of 700 lbs
✓ electronic ignition

Equipped Sensors

- ✓ NovAtel GPS,
- ✓ MicroStrain inertial sensor,
- ✓ Built in wheel odometry,
- ✓ LMS-221 laser scanner (SICK)

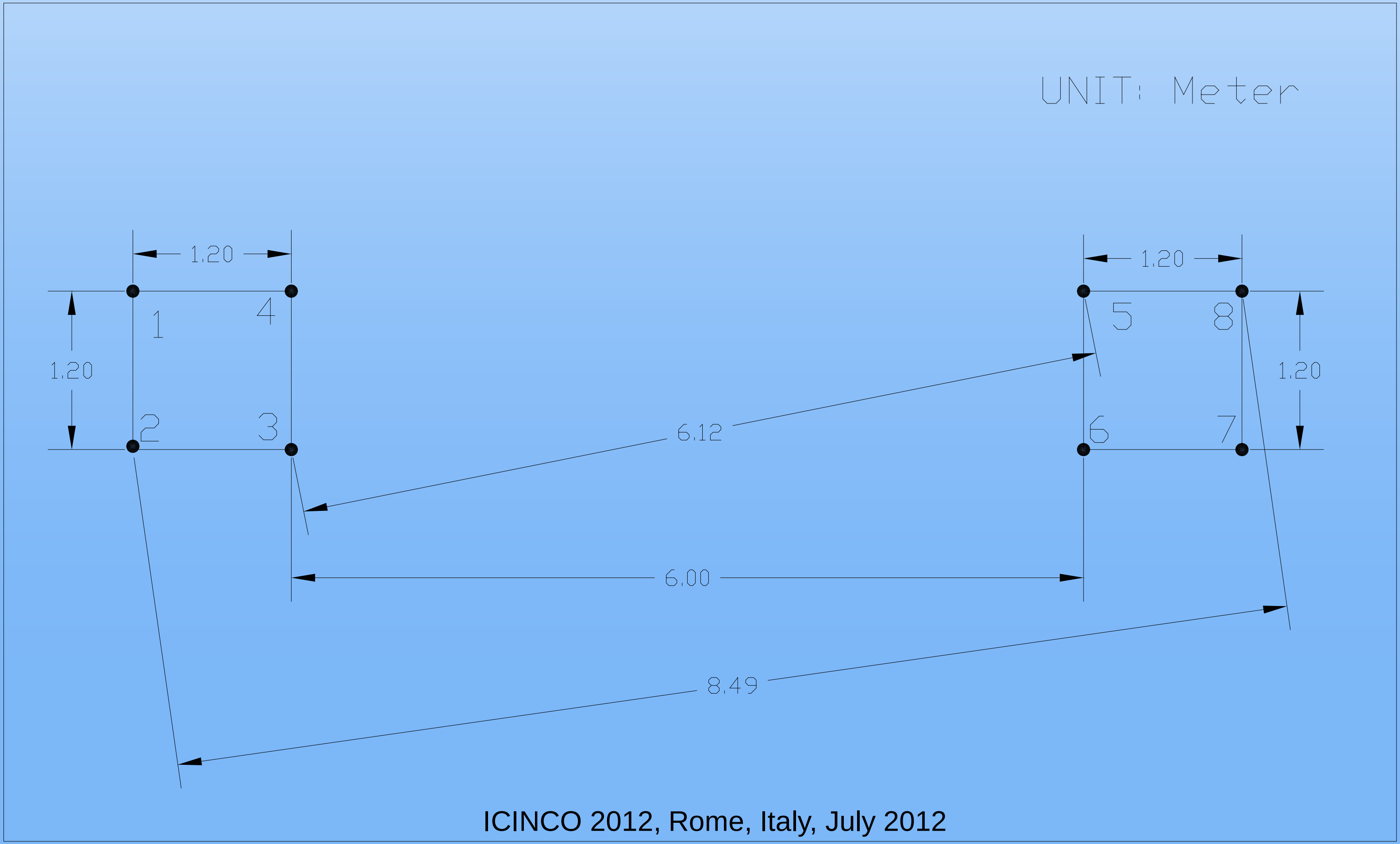
Gate Through Navigation



Location (GPS)

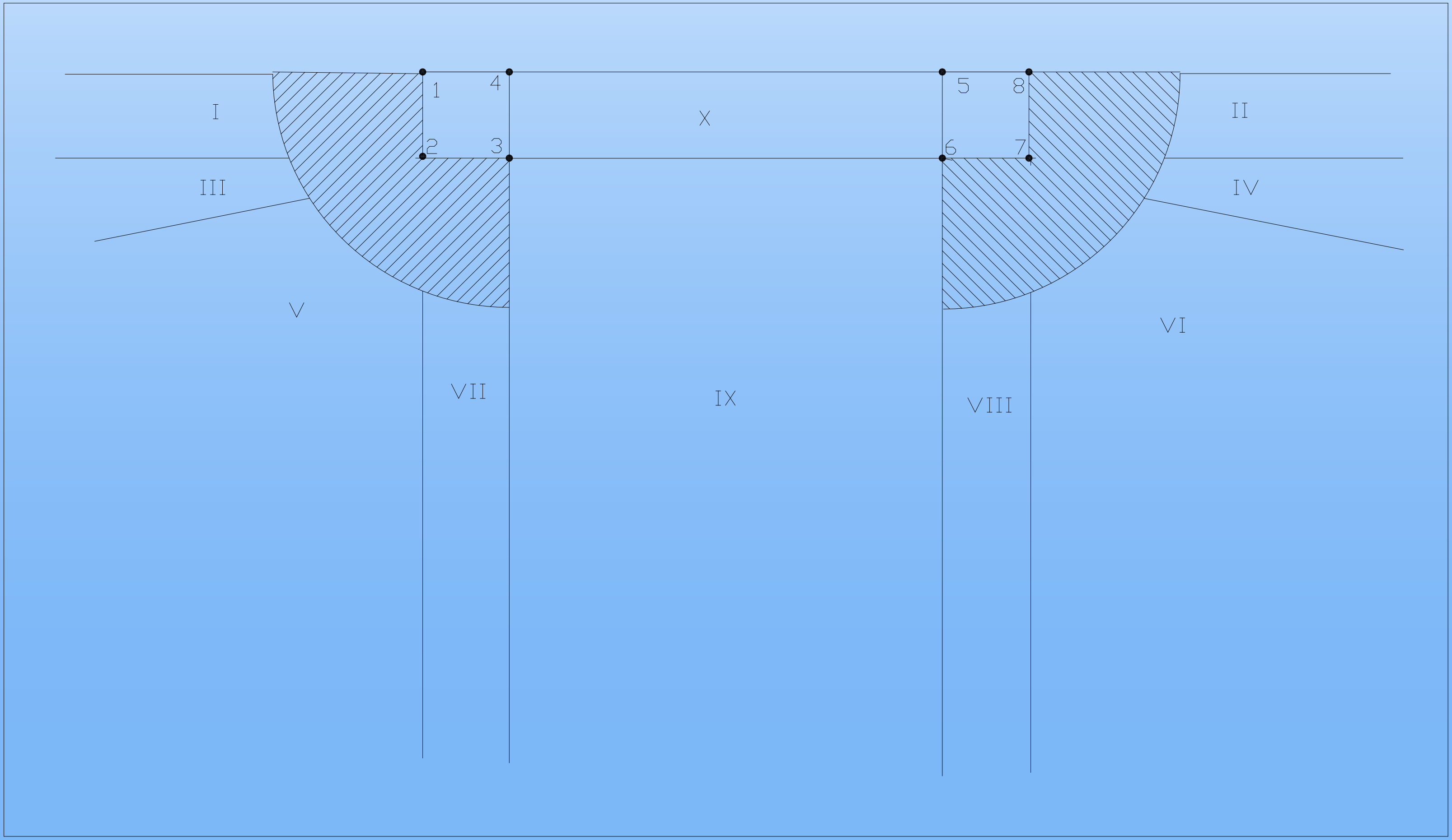
Heading (INS)

Gate Recognition



Solution for Gate Through Navigation

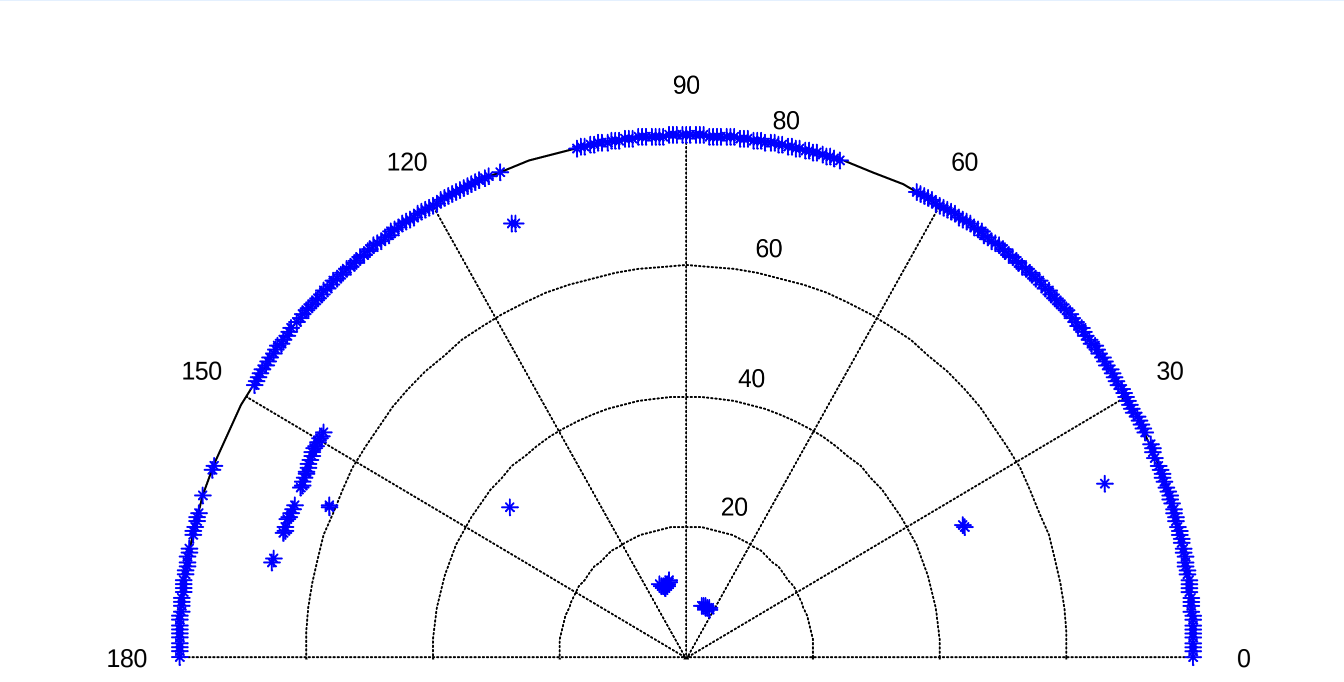
Zones of Gate Area



Visibilities of Gate Segments

Zone	Gate Segments		Zone
I	|	|	II
III	└ └	┘ ┘	IV
V	└ └	┘ ┘	VI
VII	_ └	┘ _	VIII
IX	┘ └	| |	X

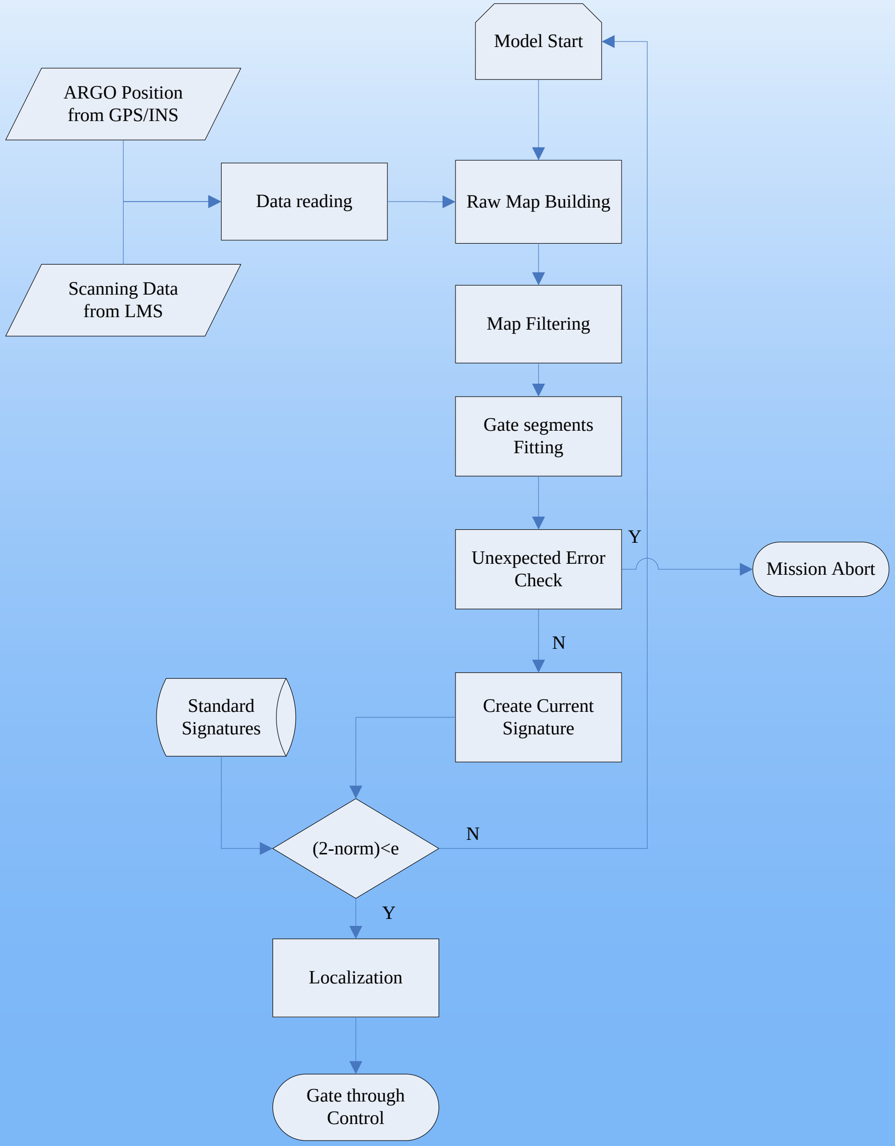
Laser Sensor Scanning



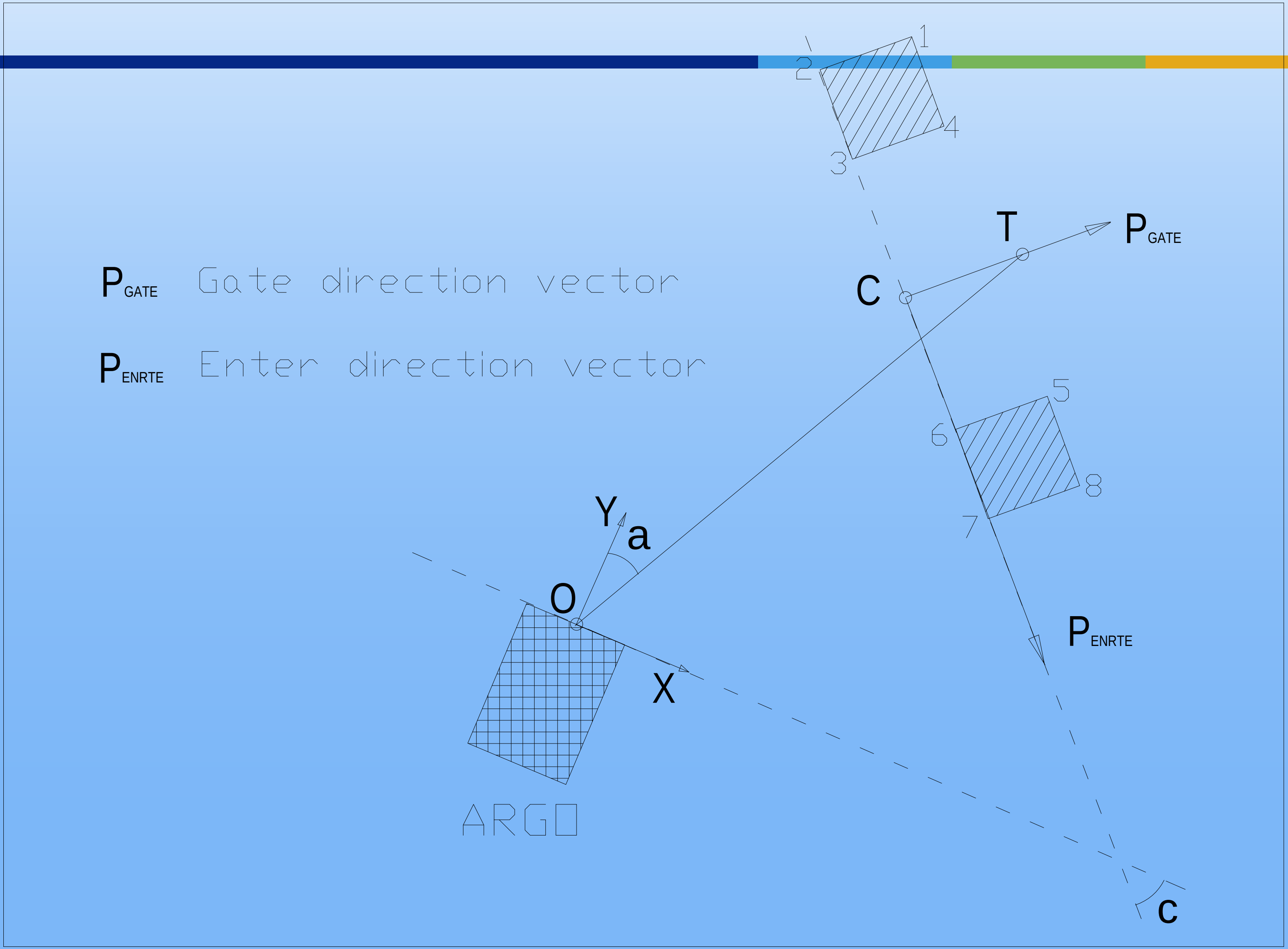
A full scan of 180° provides 361 range values

(indexed according to a scanning angle)

Flowchart of gate navigation module



Control System



Parking Control / Astolfi-controller

$$d\rho / dt = -V \cos\alpha$$

$$d\alpha / dt = V \sin\alpha / \rho - \omega$$

$$d\psi / dt = -\omega$$

or

$$V = K_{\rho}\rho$$

$$\omega = K_1\alpha + K_2\psi$$

In x-y coordinate

$$V = K_{\rho}\sqrt{x^2 + y^2}$$

$$\omega = K_1(\arctan(\frac{y}{x}) - \theta) + K_2(\frac{\pi}{2} - \theta)$$

Controller for Gate Through Navigation

$$d\rho / dt = -V \sin\psi \sin(\alpha + \psi)$$

$$d\alpha / dt = V \sin\psi \cos(\alpha + \psi) / \rho - \omega$$

$$d\psi / dt = -\omega$$

After linearization:

$$d\alpha / dt = -K_1\alpha - K_2\psi + K_\rho\psi$$

$$d\psi / dt = -K_1\alpha - K_2\psi$$

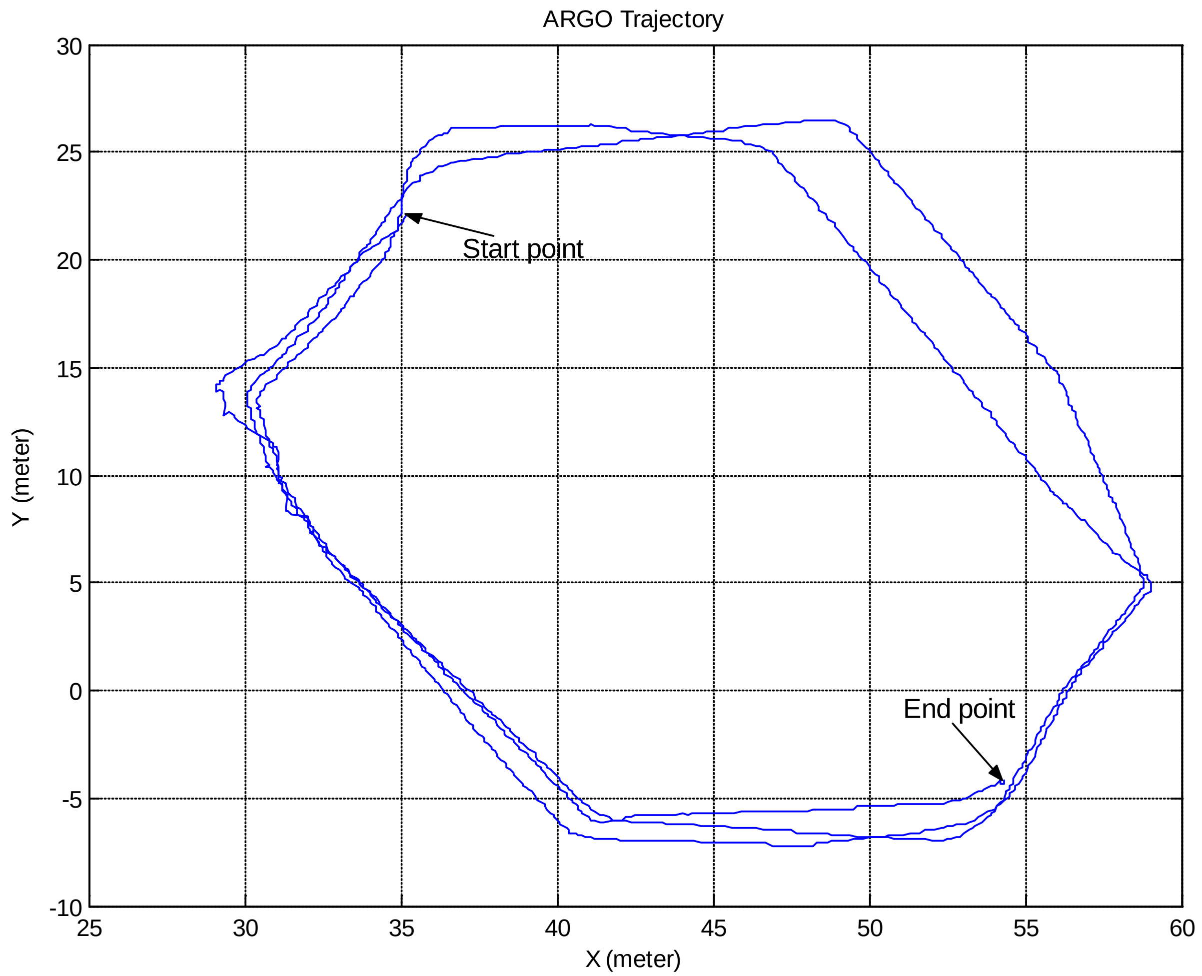
The control law is: $\omega = -K_1\alpha - K_2\psi$

The gains are experimentally set to: $K_\rho = 0.1; K_1 = 0.9; K_2 = -0.4$

α is estimated online by sensing .

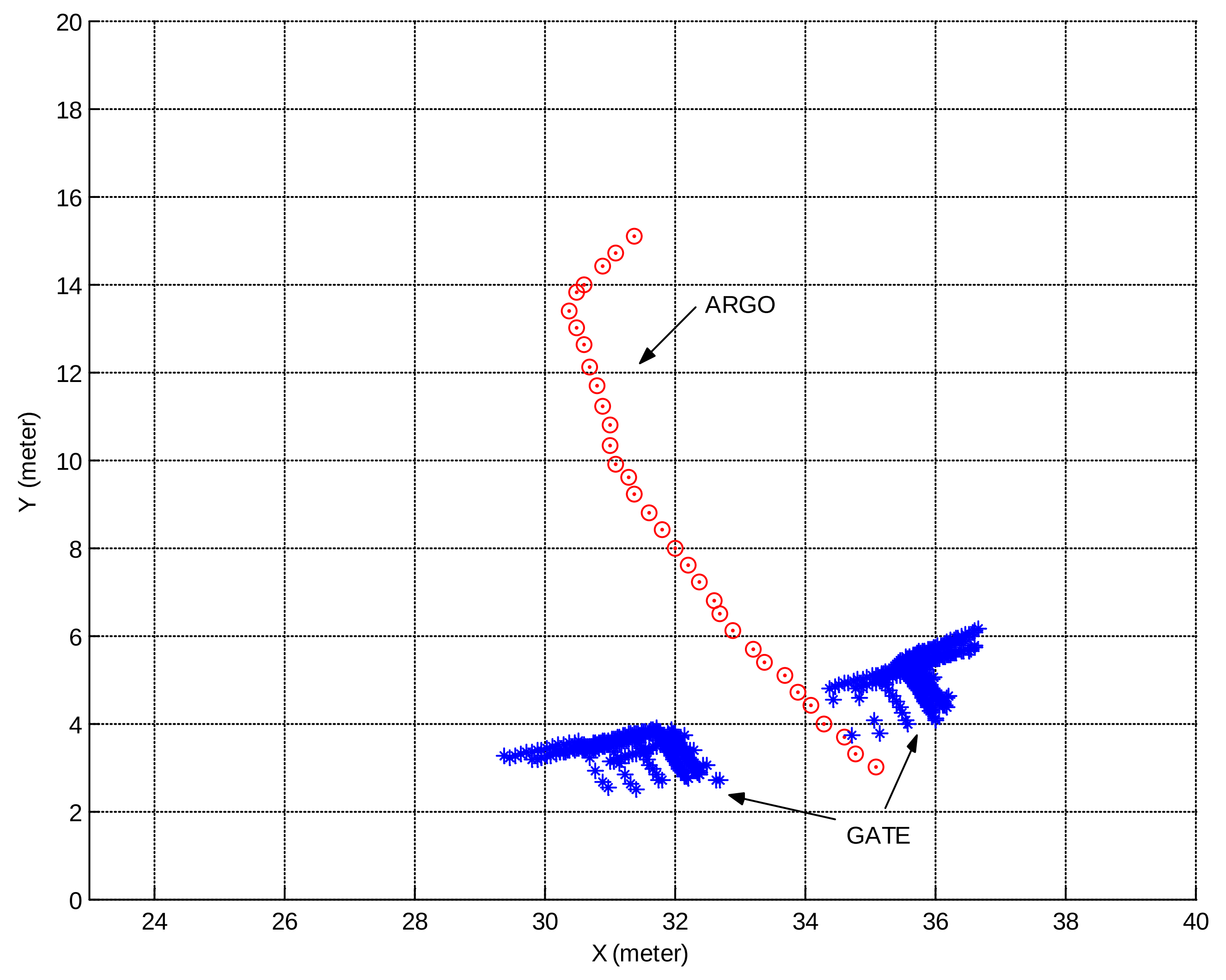
Navigation

Experimental results



Gate Through Navigation

Experimental results



Gate Through Navigation

Experimental results

Experimental results 2

Video 3

Video 4

Particle Filtering

- ☐ to estimate the robot pose:
  - measurements (scanning) from the SICK sensor are compared with the map scanning results
- ☐ robot pose estimation by particle filtering is suitable for this problem:
  - a set of hypotheses (particles) about the robot’s pose or about the locations of the objects around the robot are maintained

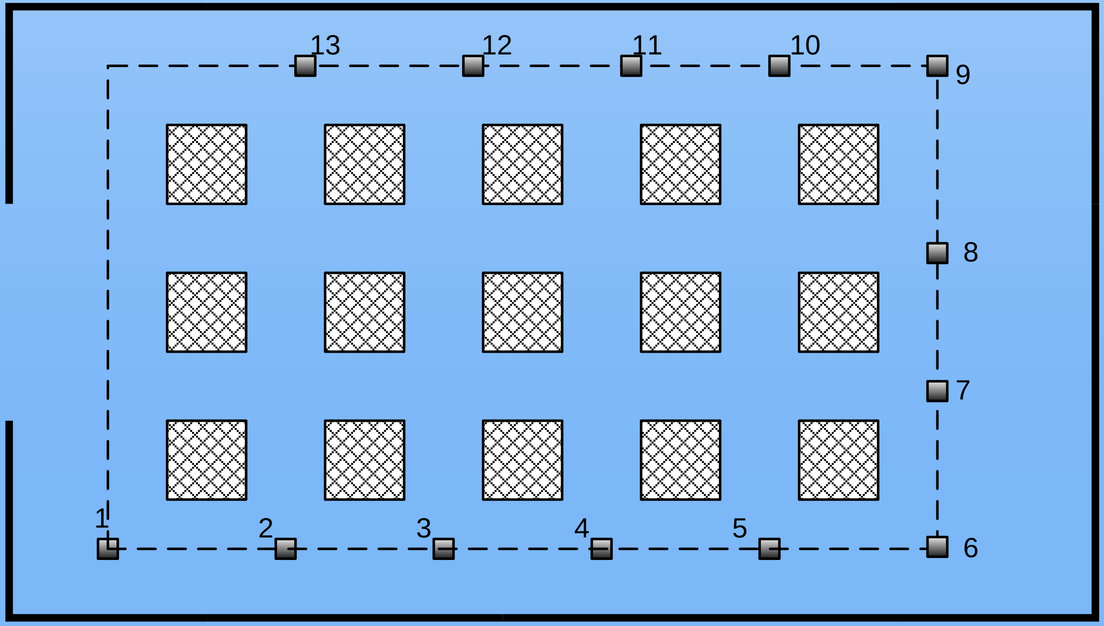
Particle Filtering

❑ particle filtering algorithm is divided into four steps:

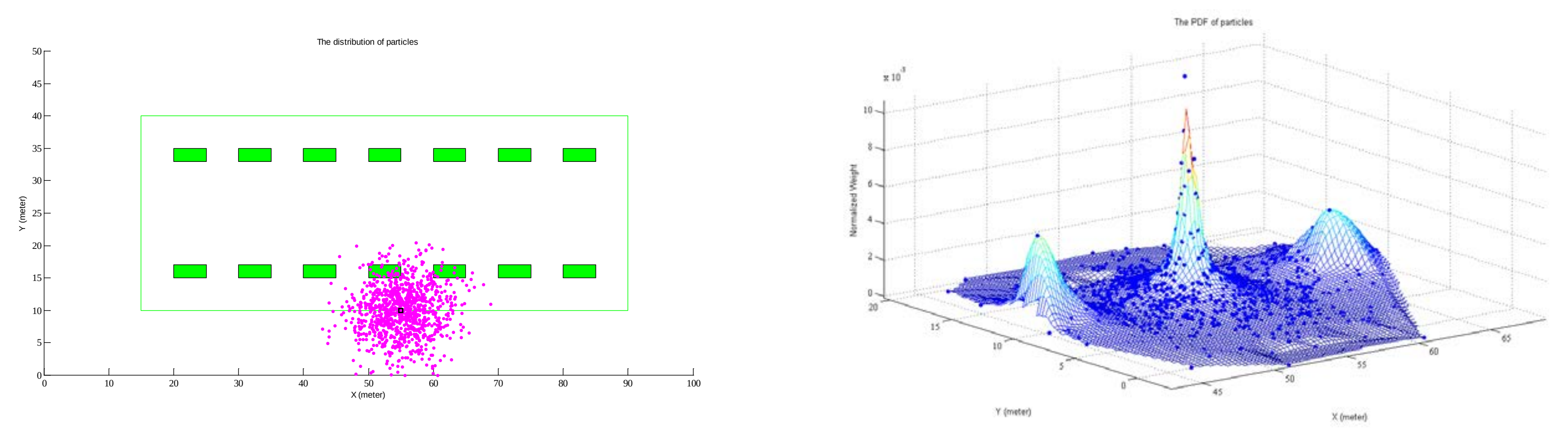
  - initial sampling;
  - prediction;
  - update;
  - re-sampling

Simulations

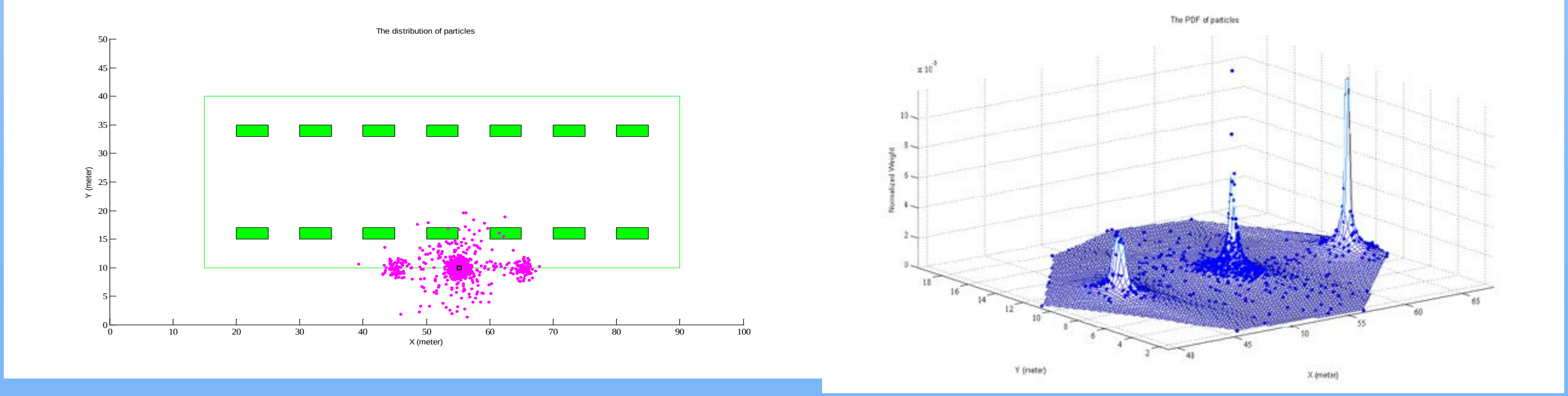
The robot running along the desired patrolling path is simulated. It is assumed that the robot has the pose information from GPS/Odometry sensor and the LRS supplies the scan data. Also, the a priori map of the environment is supposed to be known and is used to obtain the reference scan data. The robot starts from a point in the bottom edge and runs in anti-clockwise direction.



Localization with Particle Filtering

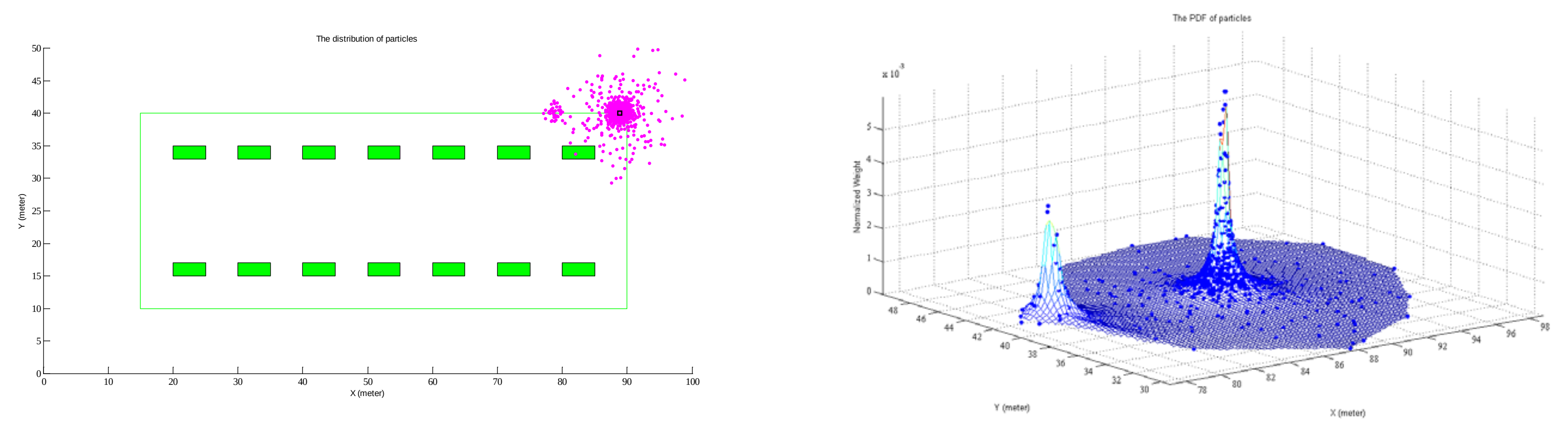


Simulation of particle filtering – initial distribution

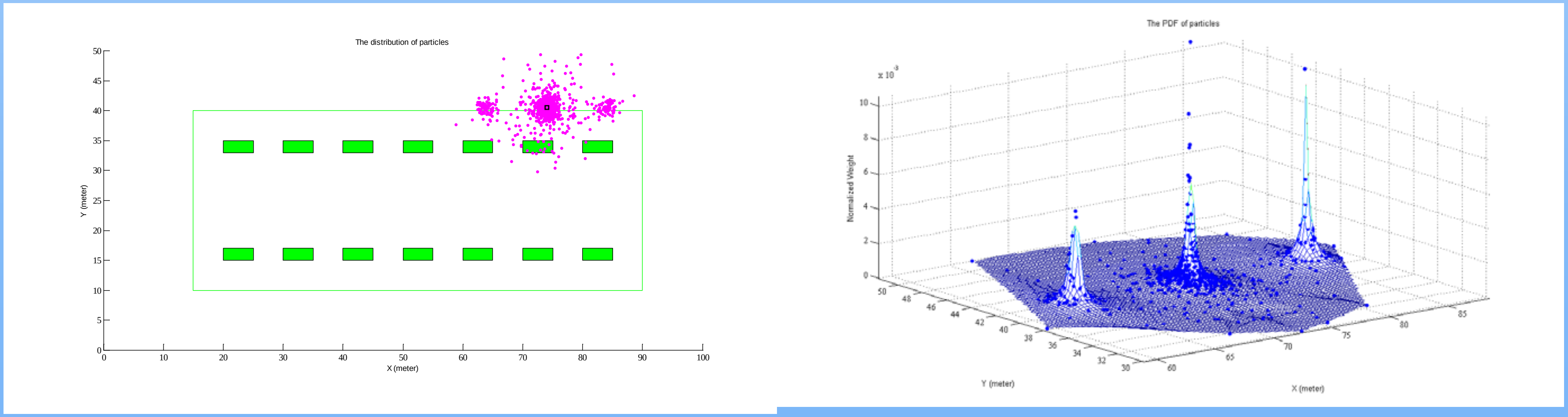


Simulation of particle filtering – re-sampling

Localization with Particle Filtering



Simulation of particle filtering – re-sampling



Simulation of particle filtering – re-sampling

Mobile Robot Navigation Using Vision

- objective
  - achieve accurate rover navigation in crowded environments
  - accurate positioning, localization, and mapping
  - fusion of odometry, inertial navigation unit (INU), and vision data,

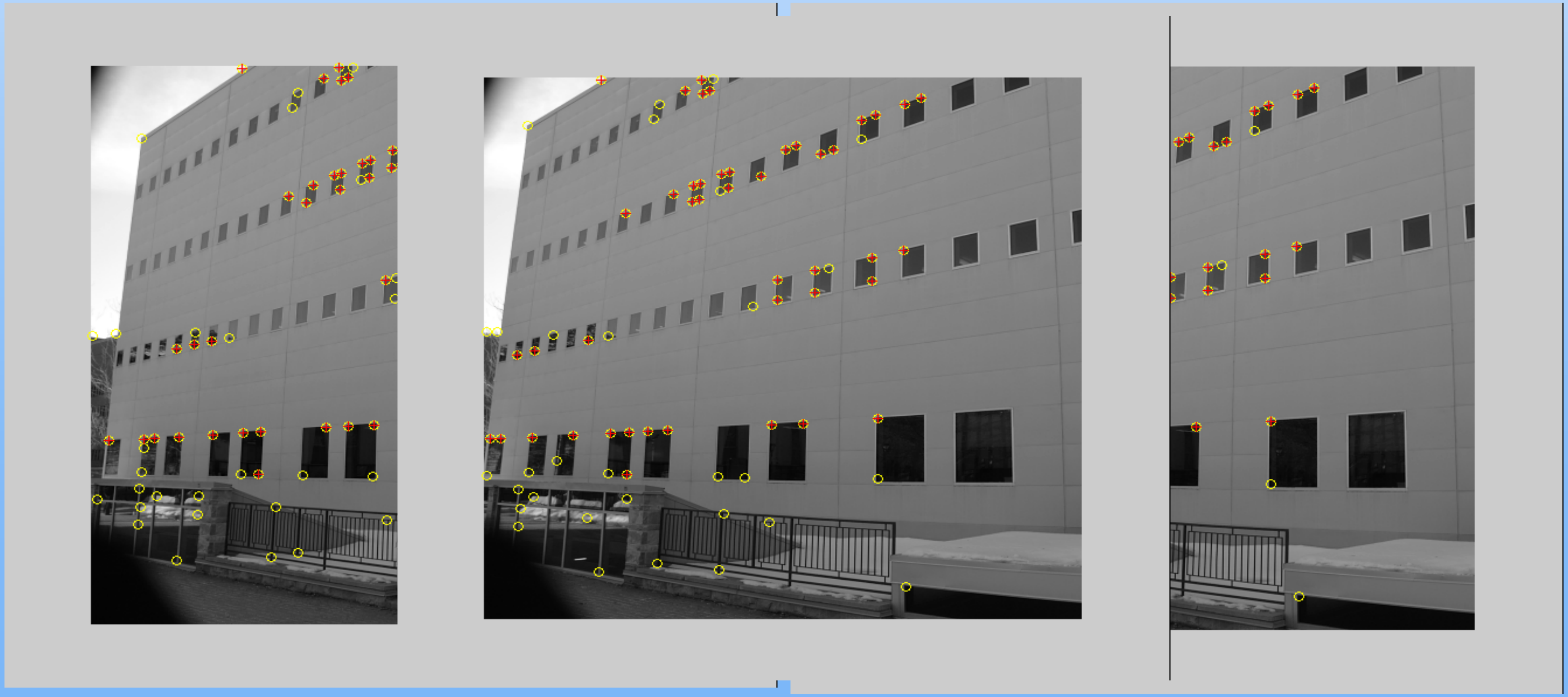
Robot Navigation Using Vision

- ❑ cameras are carried by robots
    - o can cameras be used for accurate navigation?

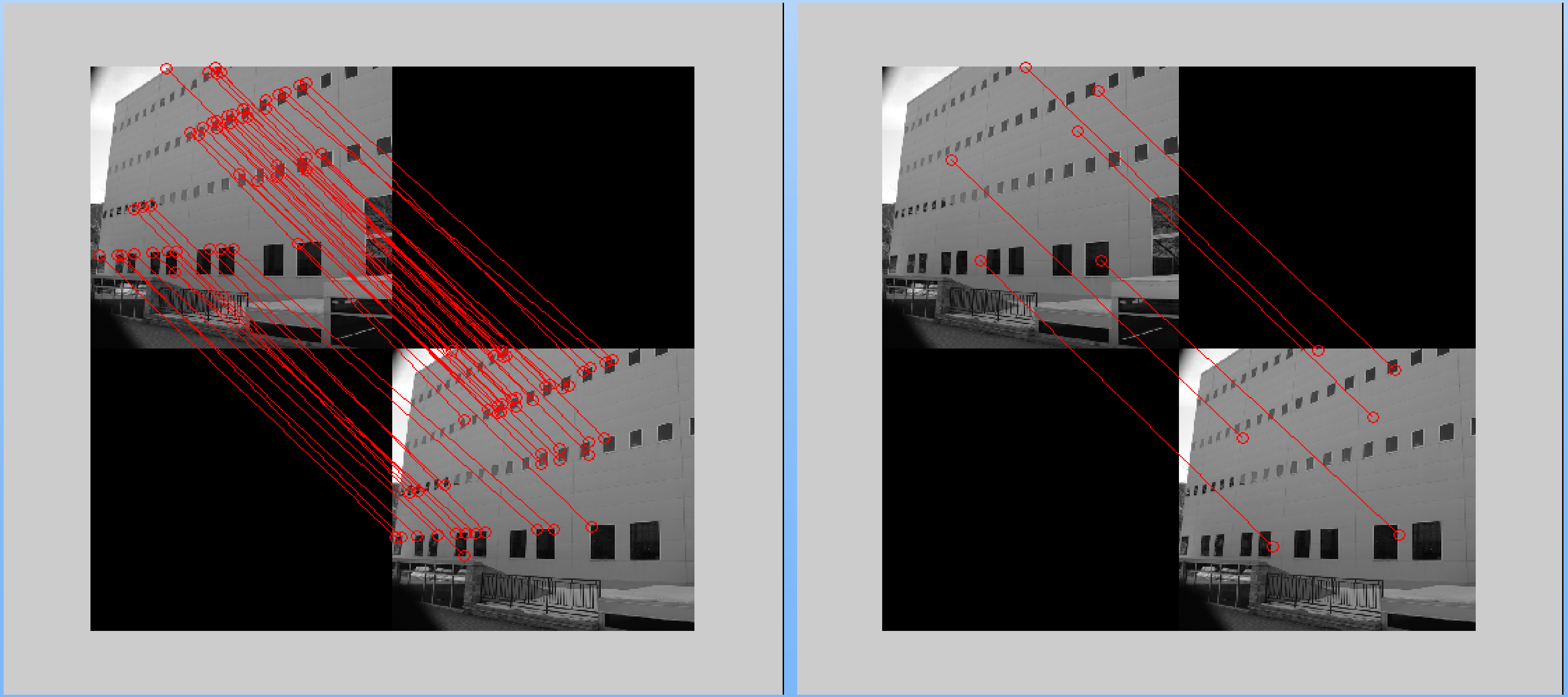
- ❑ robot position and pose come from rotation and translation of fixed camera

- ❑ key initial operation
    - o identification and localization of points-of-interest

Navigation with vision system



Navigation with vision images - correspondences



UAV Navigation Using Vision

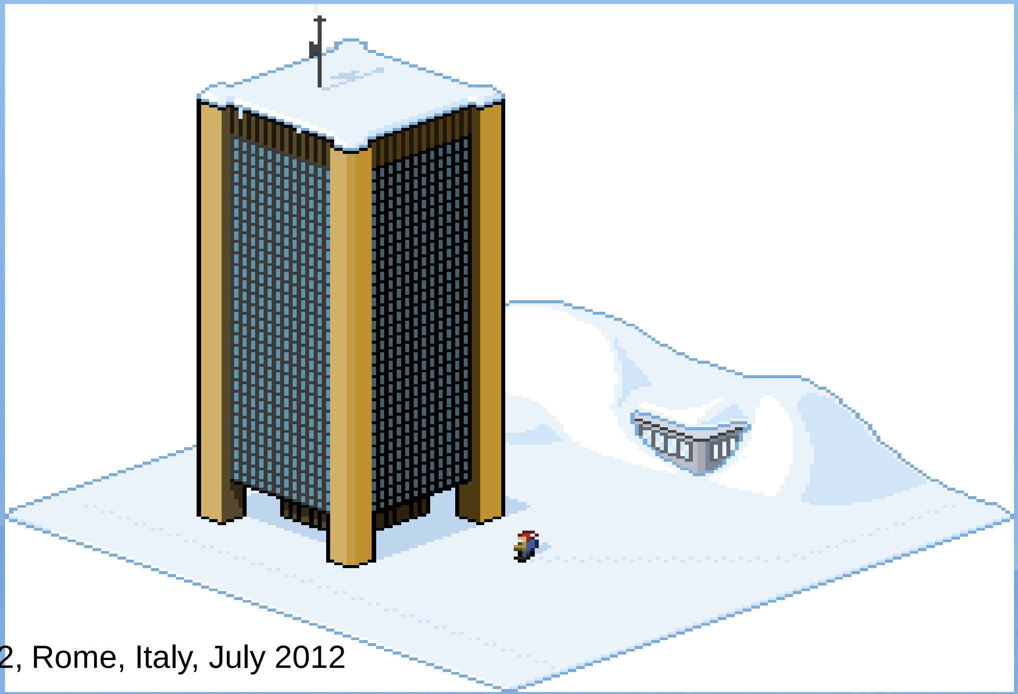
- one camera
  - motion can be derived from geometrical considerations if camera view is of points on a plane
- two cameras
  - image depth can be derived
  - rotation and translation can be derived using iterative closest point algorithm

Autonomous Vehicle Using SLAM

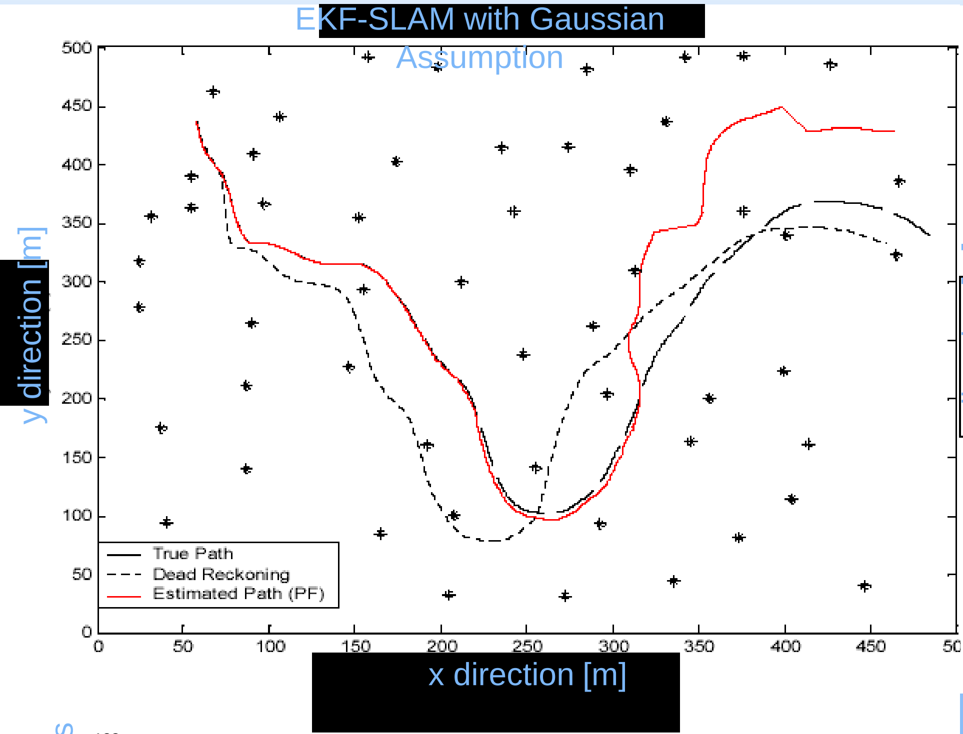
- ❑ Objective
  - o to develop an efficient navigation method for autonomous robots based on SLAM and Rao-Blackwellised particle filtering with the following considerations
    - Data association
    - Computational complexity
    - Non-linear motion and sensor models

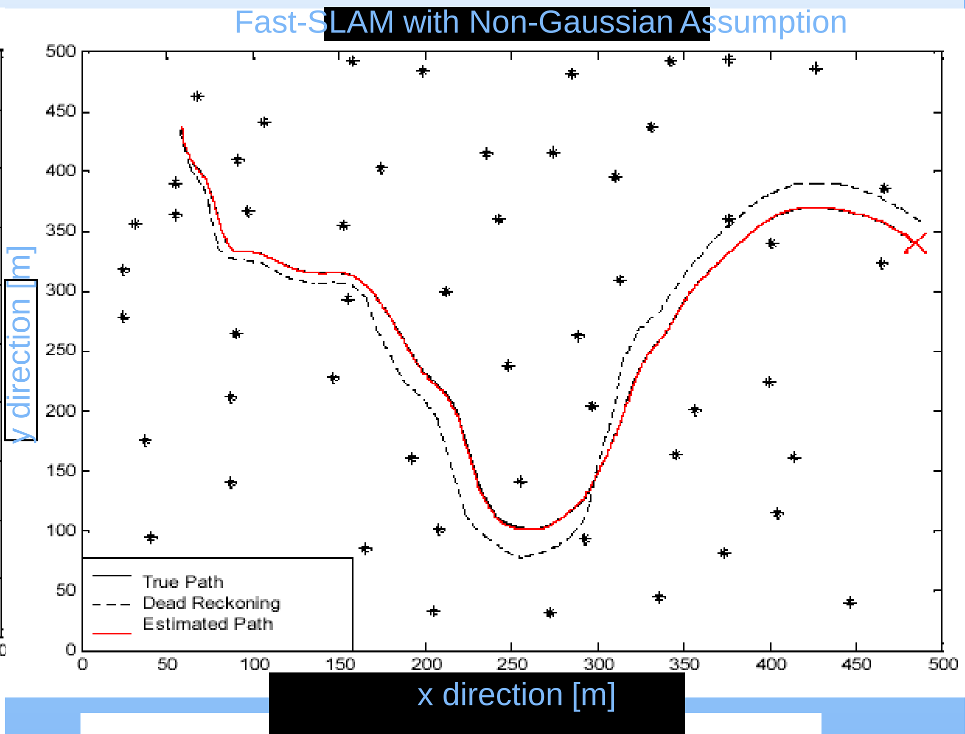
Simultaneous Localization and Mapping

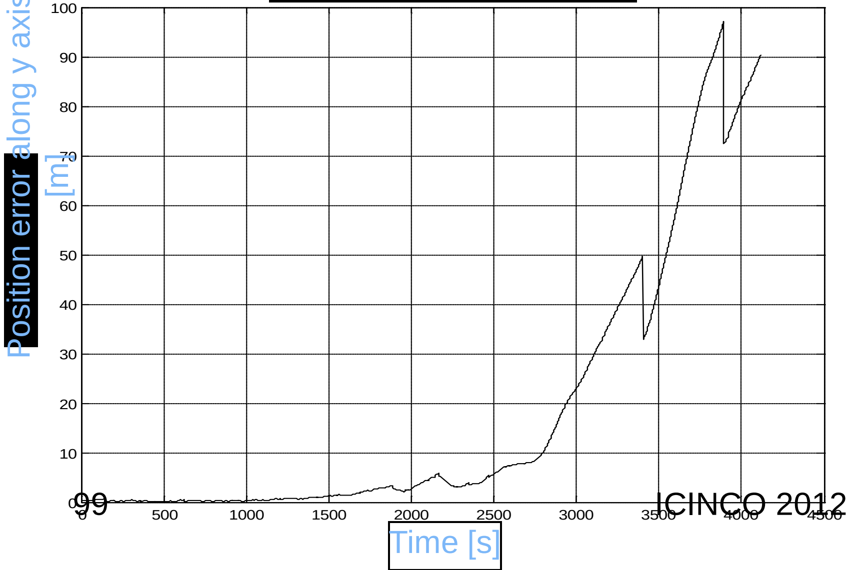
- what does the environment look like?
- where am I?
- where am I supposed to go?
- how can I get there?

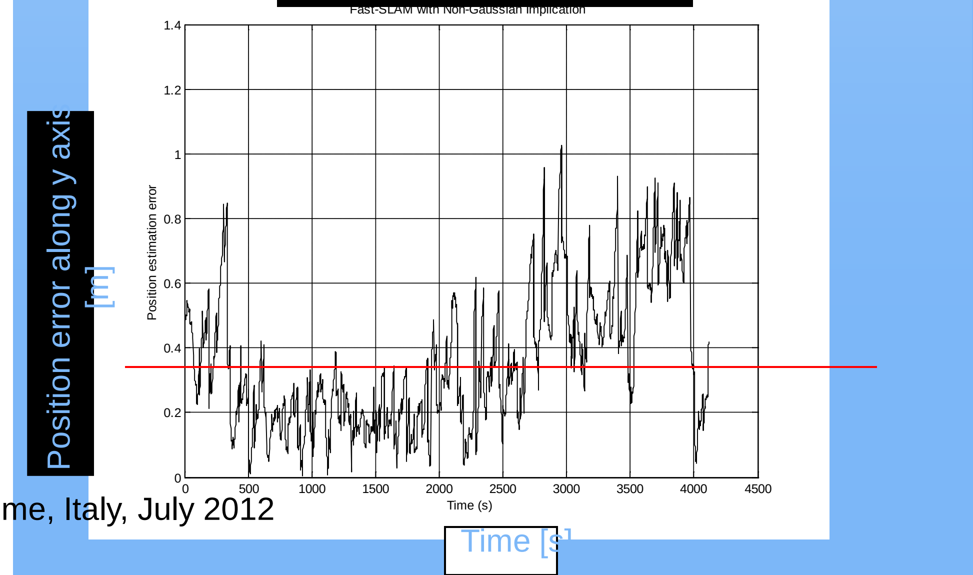


A Comparison between EKF-SLAM and Fast-SLAM





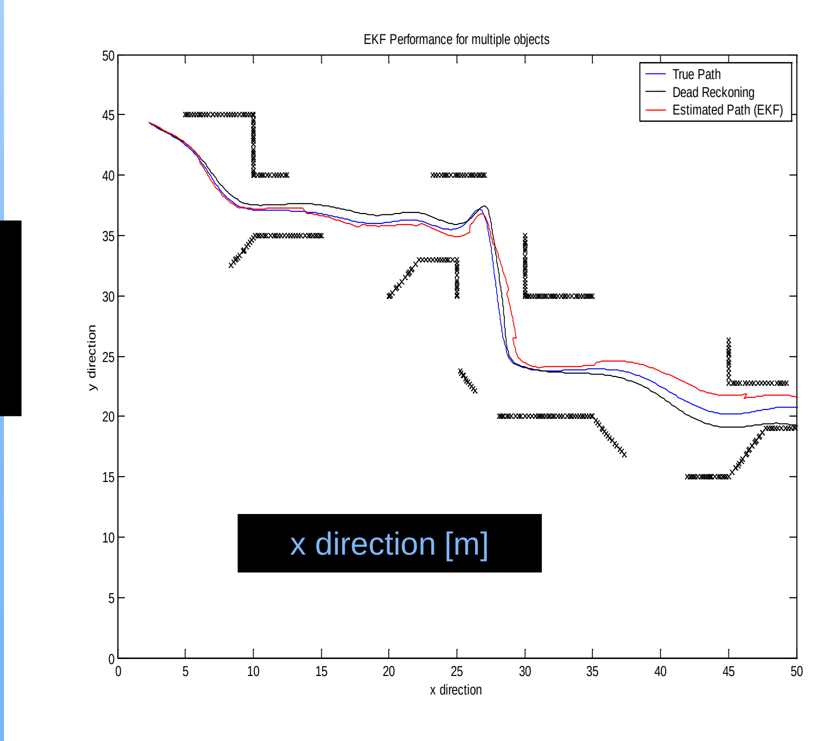




FAST-SLAM Vs. EKF-SLAM in a Dense Map for Multiple Objects (750 Landmarks)

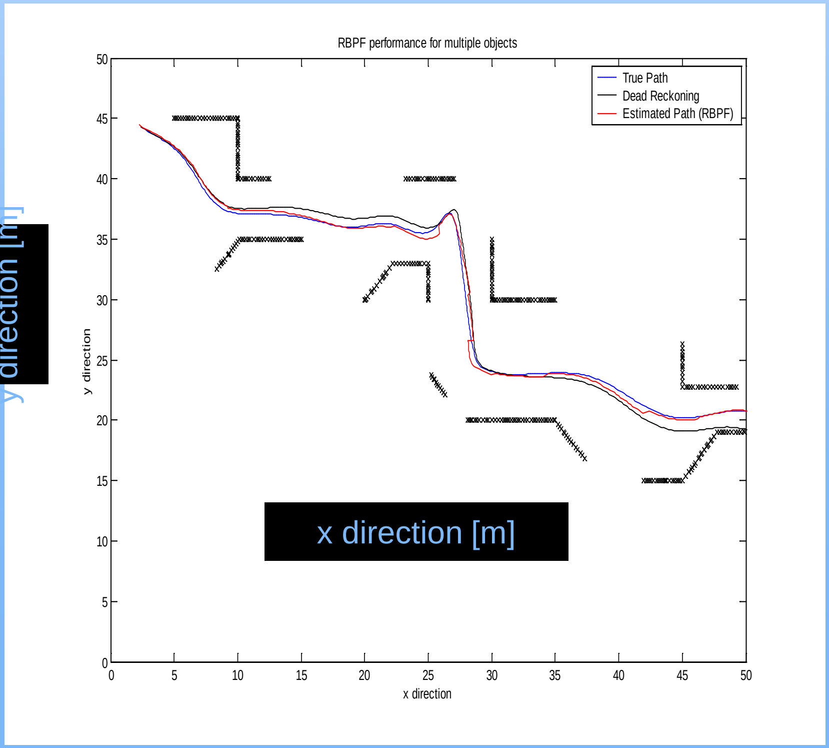
EKF-SLAM

FAST-SLAM



y direction [m]

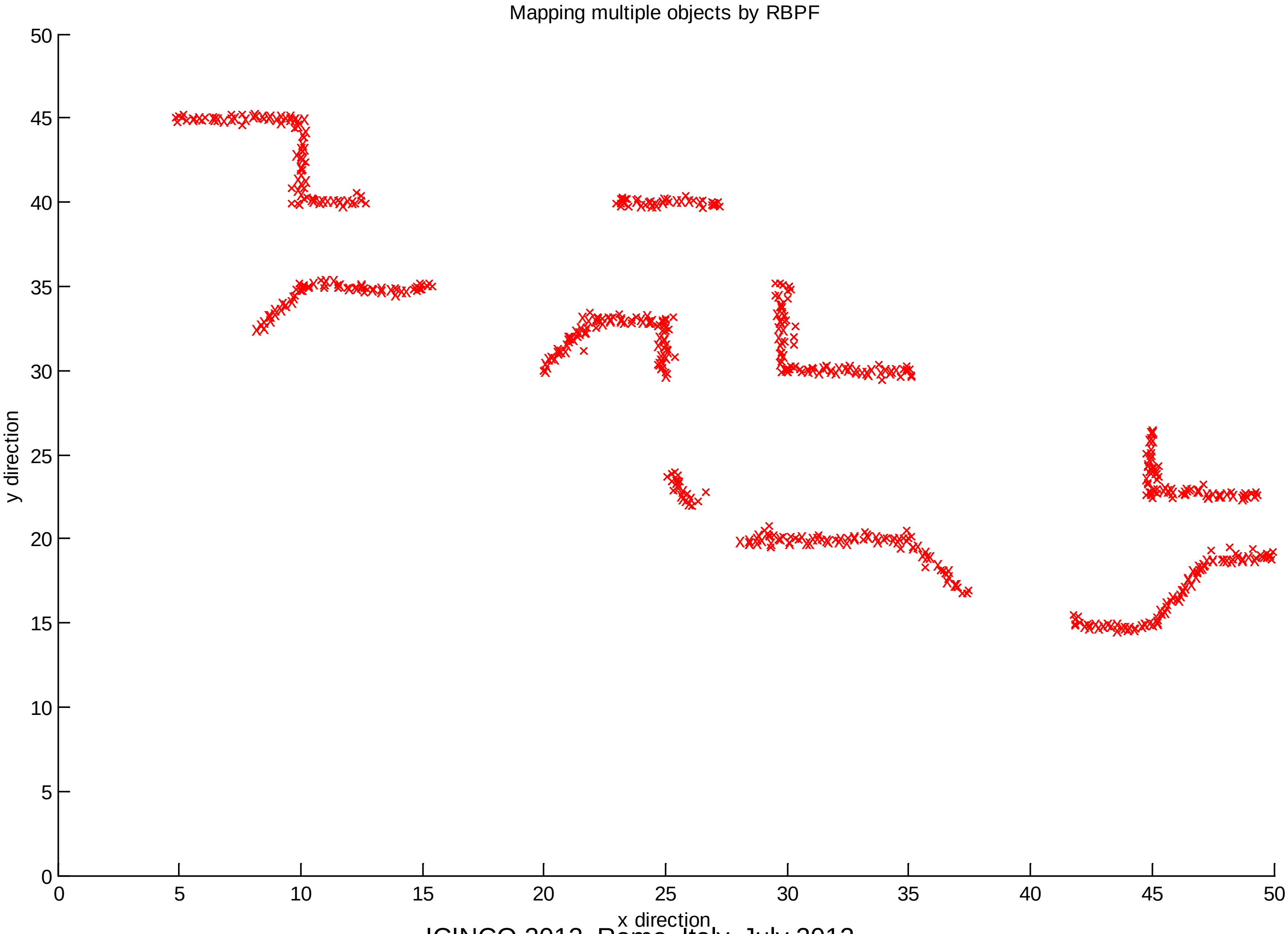
x direction [m]



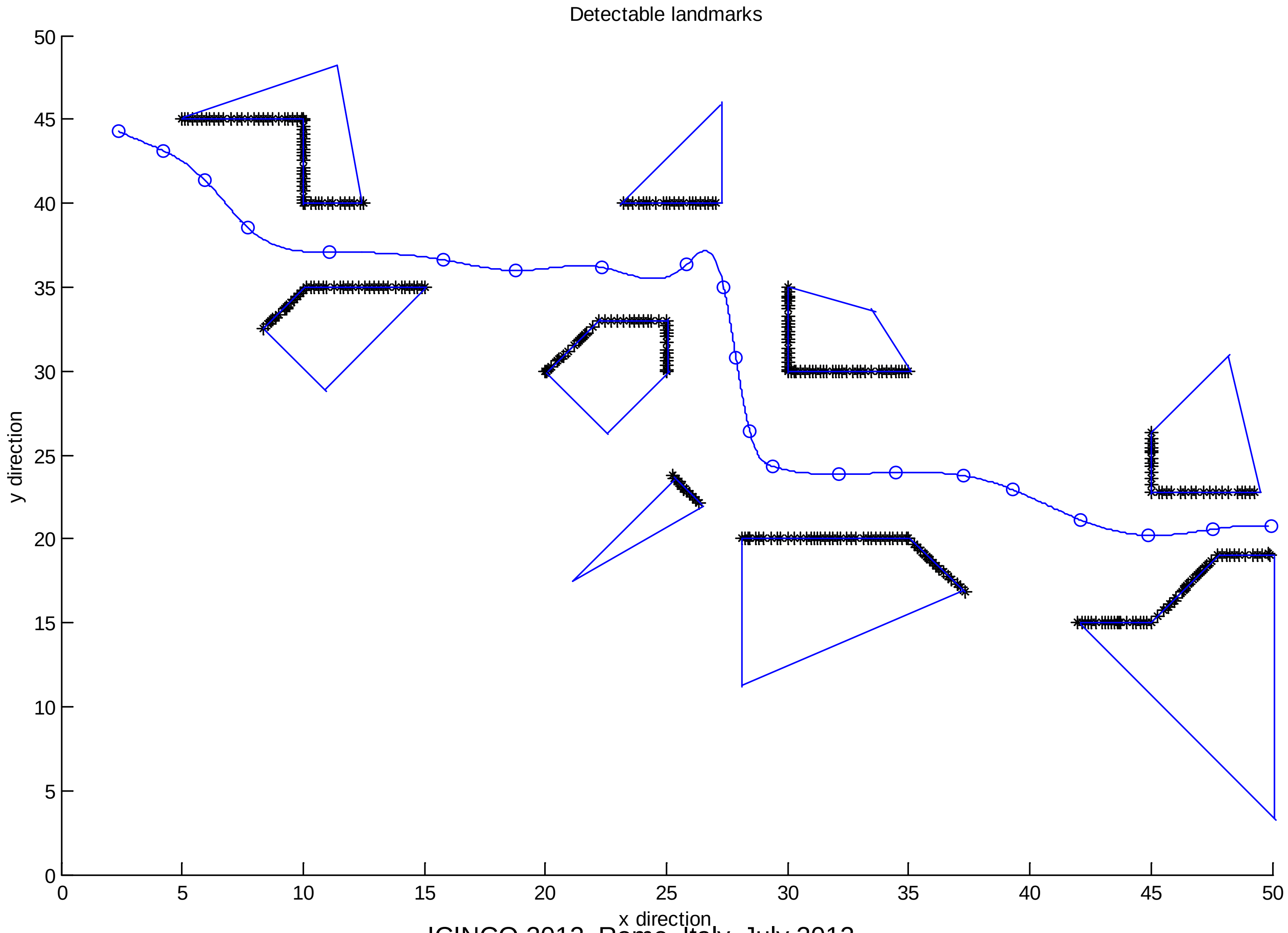
y direction [m]

x direction [m]

Fast-SLAM vs. EKF-SLAM in a Dense Map for Multiple Objects (750 Landmarks)



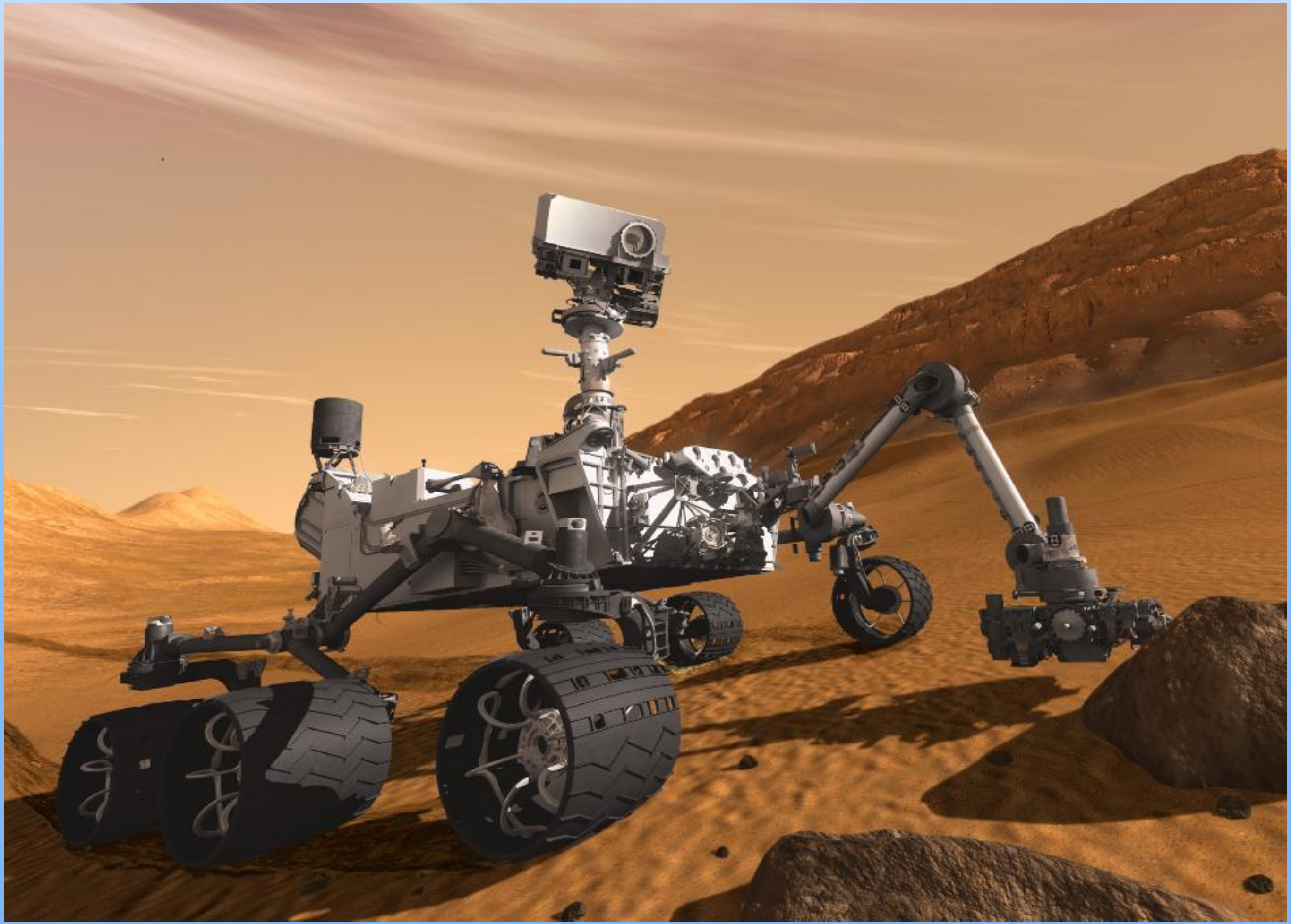
FAST-SLAM Vs. EKF-SLAM in a Dense Map for Multiple Objects (750 Landmarks)



Conclusions

- Space robotics includes many control challenges;
- Present applications of robots in Space are not fully autonomous;
- Full autonomous operations should be our objective.

Follow your Curiosity!



Acknowledgement

- Images courtesy of Canadian Space Agency and NASA or from sites:
- www. csa.ca
- www.nasa.gov
- www.oldrobots.com

Thank you !

Questions?