上海科技大学
ShanghaiTech University

CS283: **Robotics Spring 2024: Sensors**

Sören Schwertfeger

ShanghaiTech University

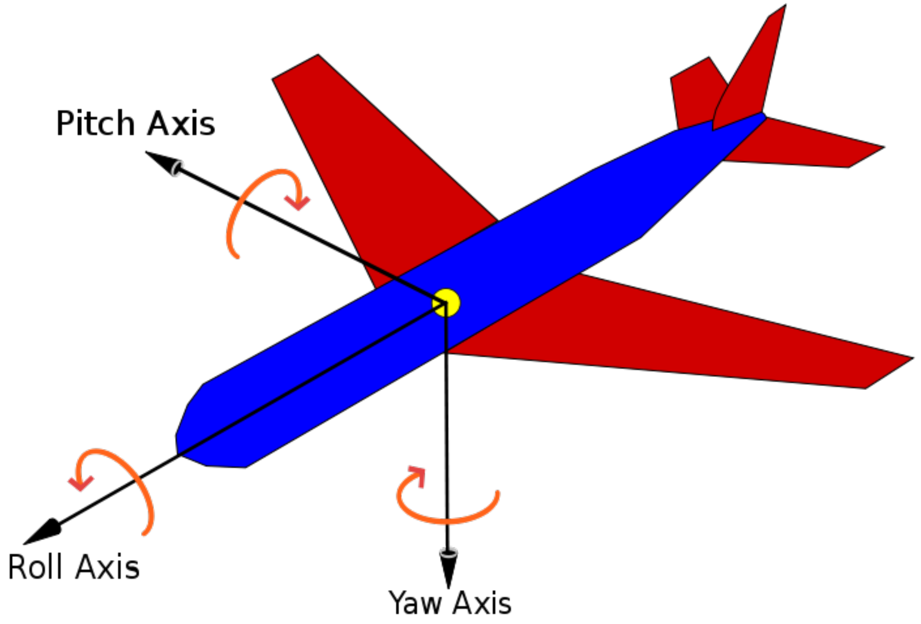
KINEMATICS CONTINUED

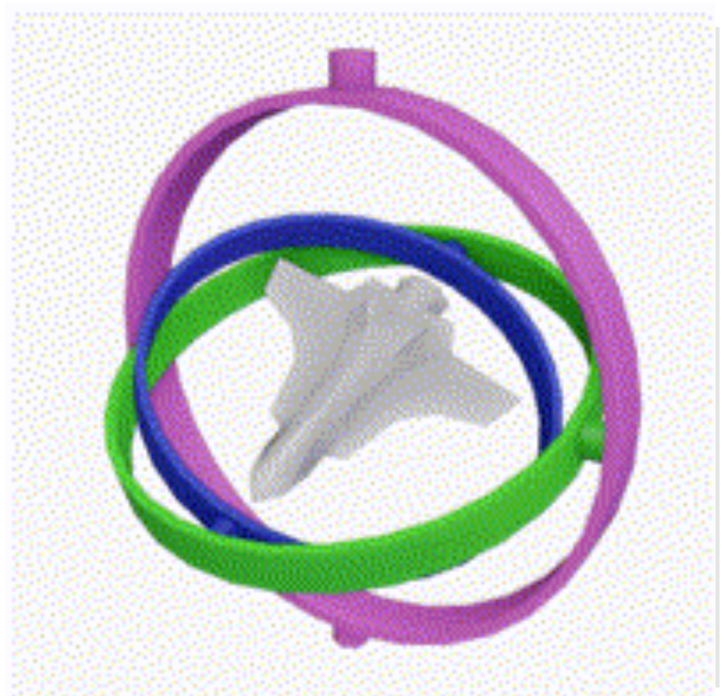
3D Rotation

- Many 3D rotation representations:

https://en.wikipedia.org/wiki/Rotation_formalisms_in_three_dimensions

- Euler angles:
  - Roll: rotation around x-axis
  - Pitch: rotation around y-axis
  - Yaw: rotation around z-axis
  - Apply rotations one after the other…
    - => Order important! E.g.:
      - x-z-x; x-y-z; z-y-x; …
  - ☹ Singularities
  - Gimbal lock in Engineering
    - "a condition caused by the collinear alignment of two or more robot axes resulting in unpredictable robot motion and velocities"





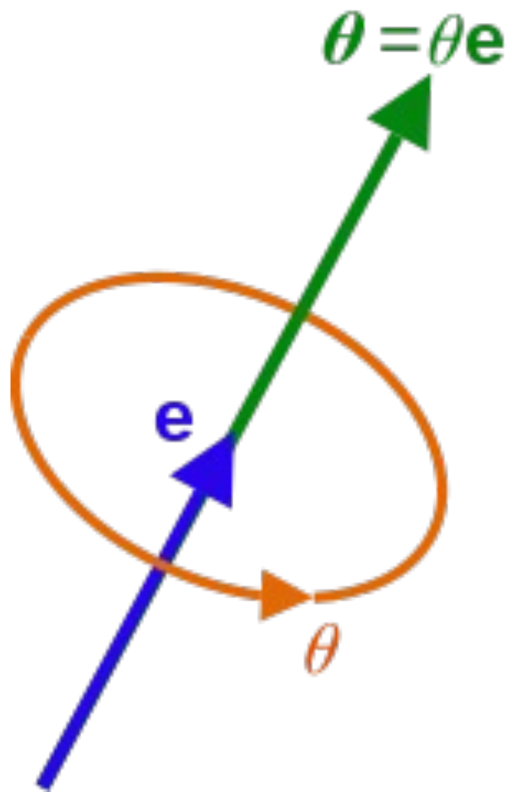
3D Rotation

- Axis Angle
  - Angle θ and
  - Axis unit vector **e** (3D vector with length 1)
    - Can be represented with 2 numbers (e.g. elevation and azimuth angles)

- Euler Angles: sequence of 3 rotations around coordinate axes

  equivalent to:

- Axis Angle: pure rotation around a single fixed axis

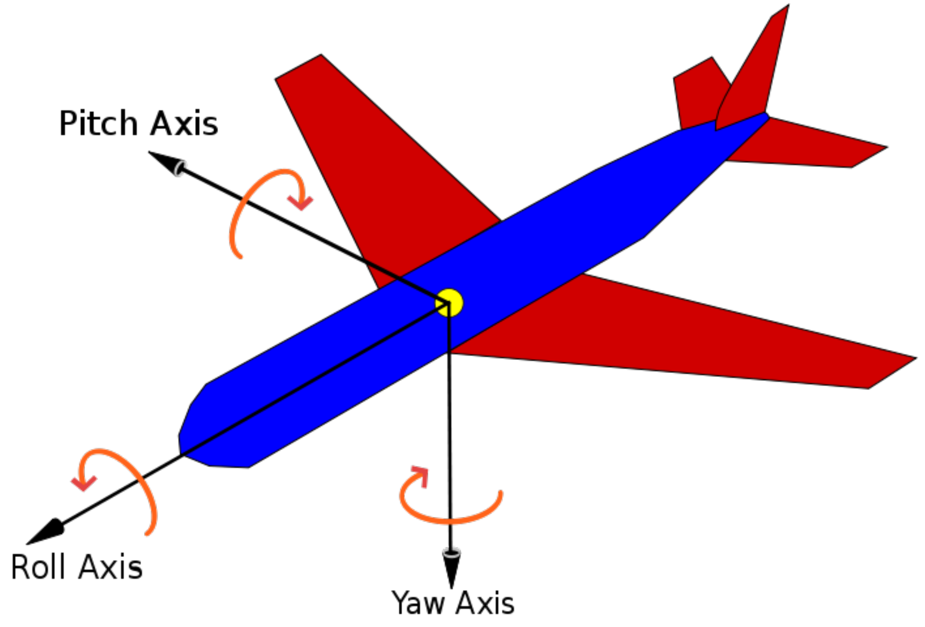


3D Rotation

- Quaternions:
  - Concatenating rotations is computationally faster and numerically more stable
  - Extracting the angle and axis of rotation is simpler
  - Interpolation is more straightforward
  - Unit Quaternion: norm = 1
    - Versor: https://en.wikipedia.org/wiki/Versor

https://en.wikipedia.org/wiki/Quaternions_and_spatial_rotation

  - Scalar (real) part: q_0 , sometimes q_w
  - Vector (imaginary) part: q
  - Over determined: 4 variables for 3 DoF (but: unit!)



$$\check{\mathbf{p}} \equiv p_0 + p_x\mathbf{i} + p_y\mathbf{j} + p_z\mathbf{k}$$

$$\mathbf{i}^2 = \mathbf{j}^2 = \mathbf{k}^2 = \mathbf{ijk} = -1$$

$$\check{\mathbf{q}} = \begin{pmatrix} q_0 & q_x & q_y & q_z \end{pmatrix}^\mathsf{T} \equiv \begin{pmatrix} q_0 \\ \mathbf{q} \end{pmatrix}$$

- Check out: https://eater.net/quaternions ! Excellent interactive video…

Transform in 3D

Matrix Euler Quaternion

$$ {}^{G}_{A}\mathbf{T} = \begin{bmatrix} {}^{G}_{A}\mathrm{R} & {}^{G}_{A}\mathrm{t} \\ 0_{1\mathrm{x}3} & 1 \end{bmatrix} = \begin{pmatrix} {}^{G}_{A}\mathrm{t} \\ {}^{G}_{A}\Theta \end{pmatrix} = \begin{pmatrix} {}^{G}_{A}\mathrm{t} \\ {}^{G}_{A}\check{\mathrm{q}} \end{pmatrix} $$

$$ {}^{G}_{A}\Theta \triangleq \left(\theta_r, \theta_p, \theta_y\right)^T $$

In ROS: Quaternions! (w, x, y, z)
Uses Eigen library for Transforms

Rotation Matrix 3x3

$$ R_x(\theta) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{bmatrix} $$

$$ R_y(\theta) = \begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{bmatrix} $$

$$ R_z(\theta) = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} $$

$$ R = R_z(\alpha)\, R_y(\beta)\, R_x(\gamma) $$

yaw = α, pitch = β, roll = γ

Eigen

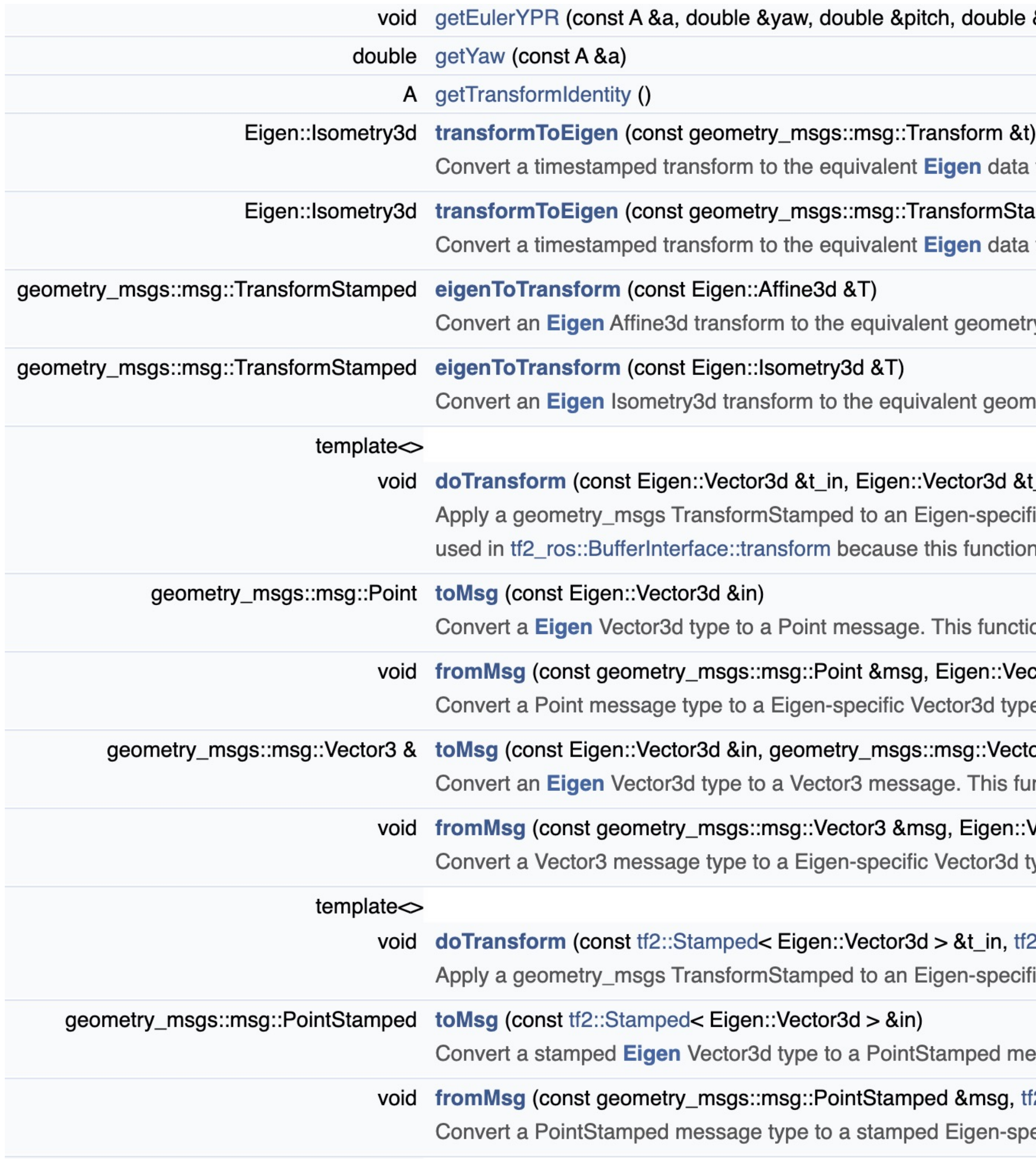
- Don't have to deal with the details of transforms too much ☺

- Conversions between ROS and Eigen:

https://docs.ros2.org/foxy/api/tf2_eigen/namespaces.html

```
Matrix3f m;
m = AngleAxisf(angle1, Vector3f::UnitZ())
    * AngleAxisf(angle2, Vector3f::UnitY())
    * AngleAxisf(angle3, Vector3f::UnitZ());
```

https://eigen.tuxfamily.org/dox/group__Geometry__Module.html



void	getEulerYPR (const A &a, double &yaw, double &pitch, double &
double	getYaw (const A &a)
A	getTransformIdentity ()
Eigen::Isometry3d	transformToEigen (const geometry_msgs::msg::Transform &t) Convert a timestamped transform to the equivalent Eigen data
Eigen::Isometry3d	transformToEigen (const geometry_msgs::msg::TransformSta Convert a timestamped transform to the equivalent Eigen data
geometry_msgs::msg::TransformStamped	eigenToTransform (const Eigen::Affine3d &T) Convert an Eigen Affine3d transform to the equivalent geometr
geometry_msgs::msg::TransformStamped	eigenToTransform (const Eigen::Isometry3d &T) Convert an Eigen Isometry3d transform to the equivalent geom
template<> void	doTransform (const Eigen::Vector3d &t_in, Eigen::Vector3d &t_ Apply a geometry_msgs TransformStamped to an Eigen-specifi used in tf2_ros::BufferInterface::transform because this function
geometry_msgs::msg::Point	toMsg (const Eigen::Vector3d &in) Convert a Eigen Vector3d type to a Point message. This functio
void	fromMsg (const geometry_msgs::msg::Point &msg, Eigen::Vec Convert a Point message type to a Eigen-specific Vector3d type
geometry_msgs::msg::Vector3 &	toMsg (const Eigen::Vector3d &in, geometry_msgs::msg::Vecto Convert an Eigen Vector3d type to a Vector3 message. This fun
void	fromMsg (const geometry_msgs::msg::Vector3 &msg, Eigen::V Convert a Vector3 message type to a Eigen-specific Vector3d ty
template<> void	doTransform (const tf2::Stamped< Eigen::Vector3d > &t_in, tf2 Apply a geometry_msgs TransformStamped to an Eigen-specifi
geometry_msgs::msg::PointStamped	toMsg (const tf2::Stamped< Eigen::Vector3d > &in) Convert a stamped Eigen Vector3d type to a PointStamped me
void	fromMsg (const geometry_msgs::msg::PointStamped &msg, tf Convert a PointStamped message type to a stamped Eigen-spe

Examples of Transforms

- Transform between global coordinate frame and robot frame at time X
- Transform between robot frame at time X and robot frame at time X+1

- Transform between robot camera frame and robot base frame (mounted fixed – not dependend on time! => static transform)
- Transform between map origin and door pose in map (not time dependend)

- Transform between robot camera frame and fingers (end-effector) of a robot arm at time X
- Transform between robot camera frame and map frame at time X
- Transform between robot 1 camera at time X and robot 2 camera at time X+n

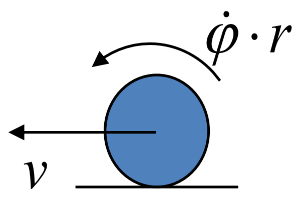
ROS Standards:

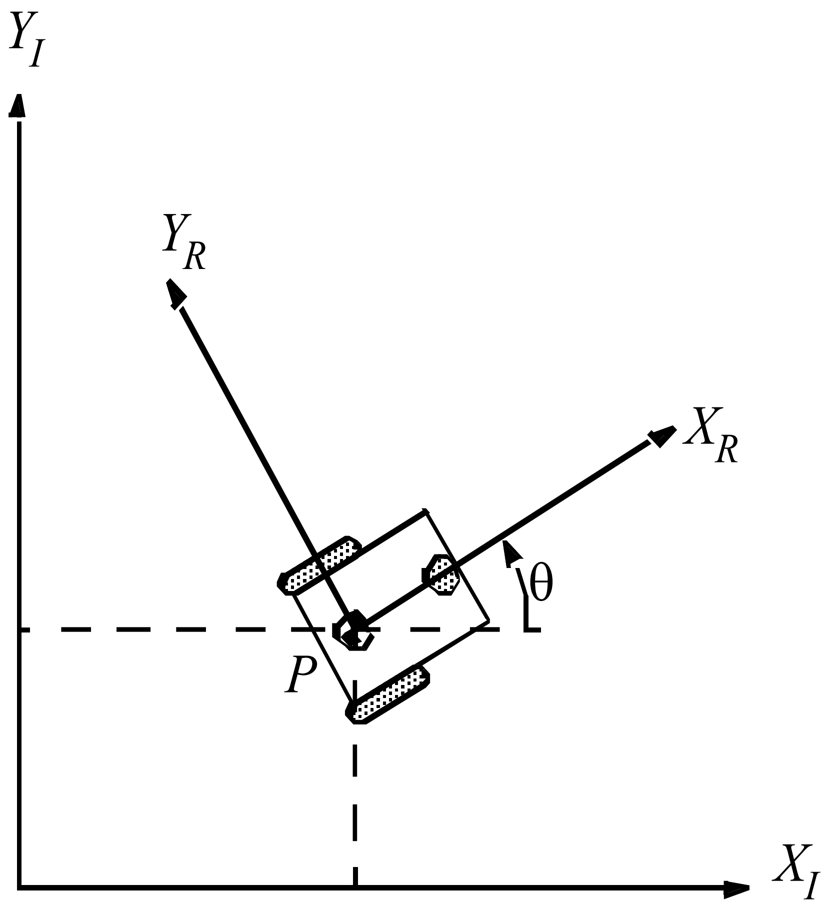
- Standard Units of Measure and Coordinate Conventions
  - http://www.ros.org/reps/rep-0103.html

- Coordinate Frames for Mobile Platforms:
  - http://www.ros.org/reps/rep-0105.html

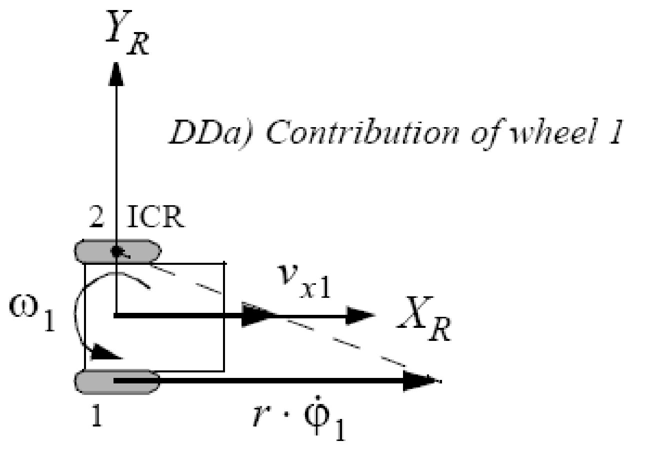
Wheel Kinematic Constraints: Assumptions

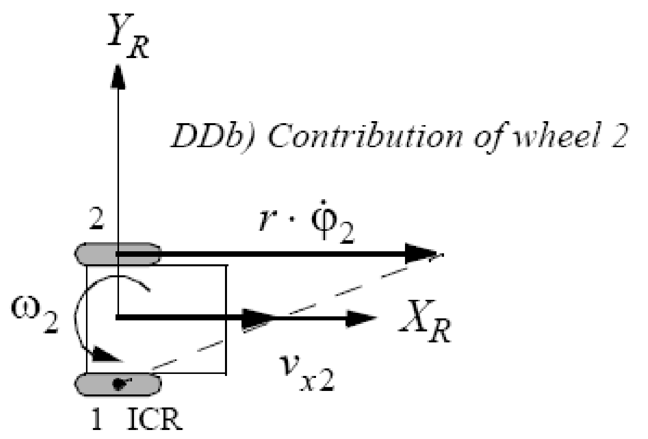
- Movement on a horizontal plane
- Point contact of the wheels
- Wheels not deformable
- Pure rolling
  - $v_c = 0$ at contact point
- No slipping, skidding or sliding
- No friction for rotation around contact point
- Steering axes orthogonal to the surface
- Wheels connected by rigid frame (chassis)





Forward Kinematic Model: Geometric Approach





Differential-Drive:

DDa) $v_{x1} = \frac{1}{2}r\dot{\varphi}_1 \quad ; \quad v_{y1} = 0 \quad ; \quad \omega_1 = \frac{1}{2l}r\dot{\varphi}_1$

DDb) $v_{x2} = \frac{1}{2}r\dot{\varphi}_2 \quad ; \quad v_{y2} = 0 \quad ; \quad \omega_2 = -\frac{1}{2l}r\dot{\varphi}_2$

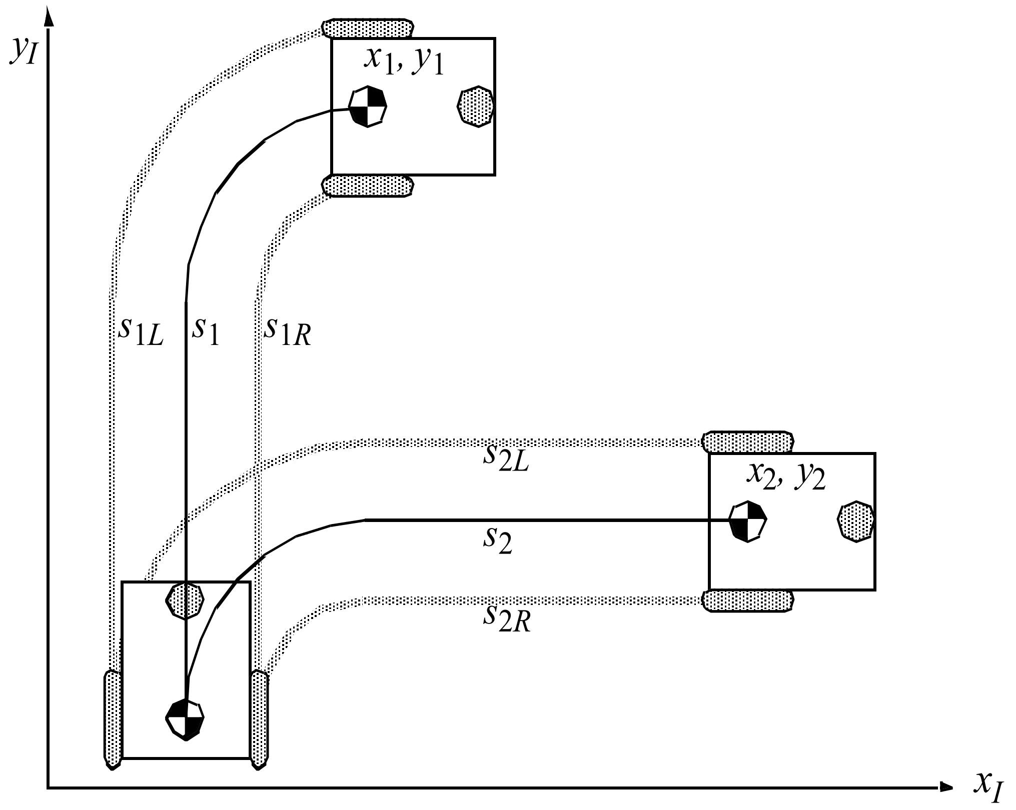
$$\text{->}\ \xi_I = \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix}_I = R(\theta)^{-1} \begin{bmatrix} v_{x1} + v_{x2} \\ v_{y1} + v_{y2} \\ \omega_1 + \omega_2 \end{bmatrix} = R(\theta)^{-1} \begin{bmatrix} \frac{r}{2} & \frac{r}{2} \\ 0 & 0 \\ \frac{r}{2l} & -\frac{r}{2l} \end{bmatrix} \begin{bmatrix} \dot{\varphi}_1 \\ \dot{\varphi}_2 \end{bmatrix}$$

Inverse of R => Active and Passive Transform:
http://en.wikipedia.org/wiki/Active_and_passive_transformation

Mobile Robot Kinematics: Non-Holonomic Systems

$s_1 = s_2$; $s_{1R} = s_{2R}$; $s_{1L} = s_{2L}$

but: $x_1 \neq x_2$; $y_1 \neq y_2$



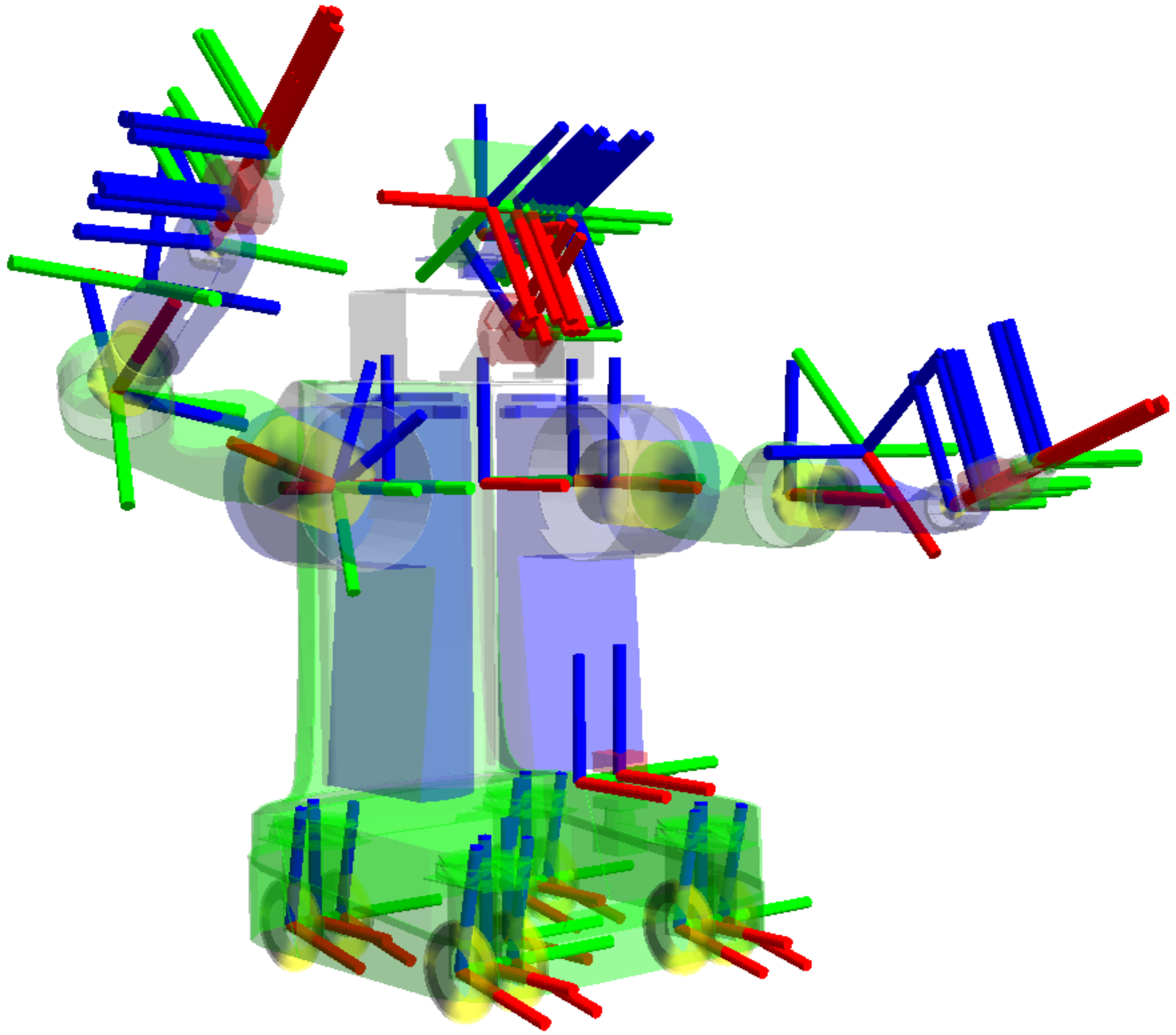
- Non-holonomic systems
  - differential equations are not integrable to the final pose.
  - the measure of the traveled distance of each wheel is not sufficient to calculate the final position of the robot. One has also to know how this movement was executed as a function of time.

Holonomic examples

Uranus, CMU

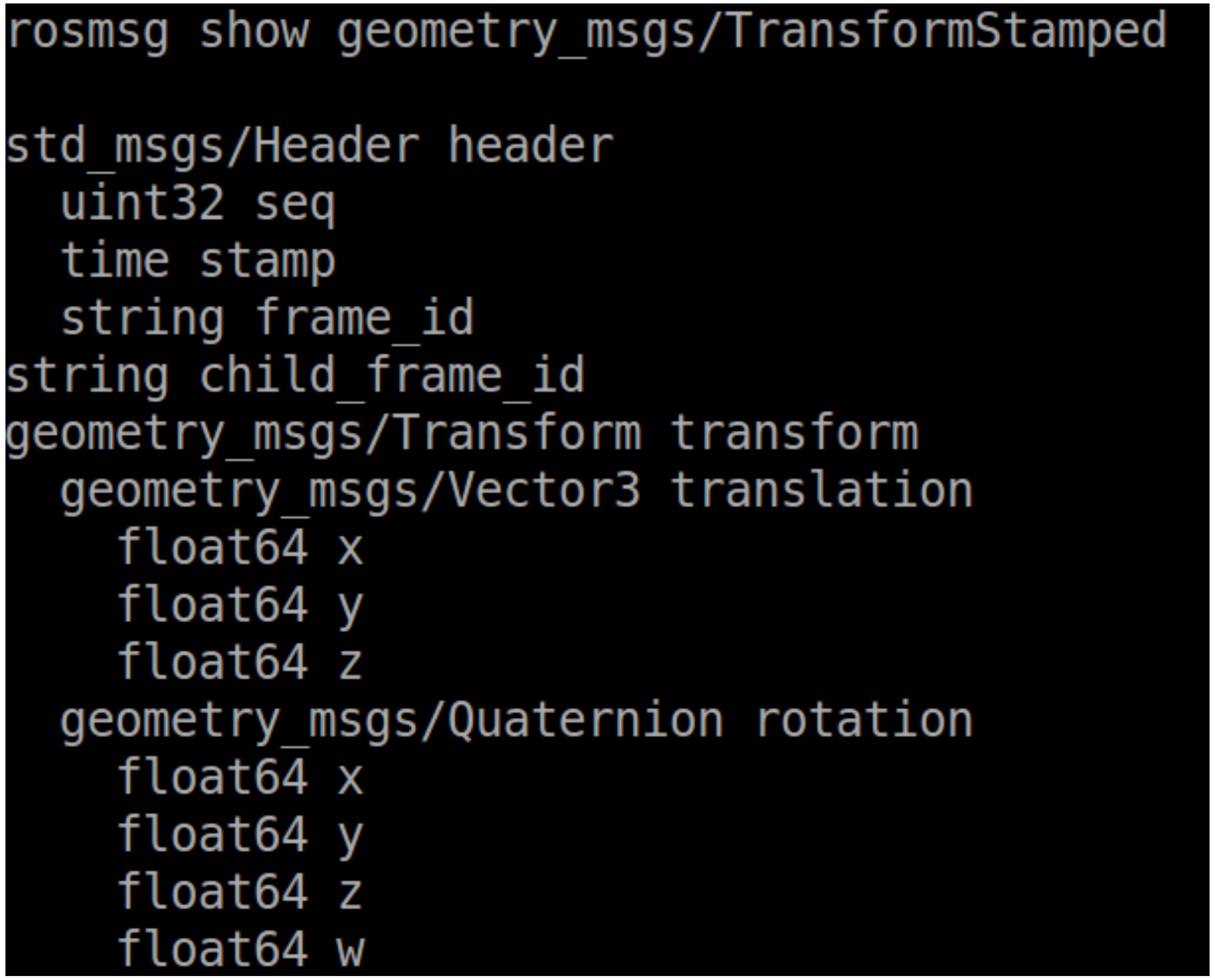
ROS: 3D Transforms : TF

- http://wiki.ros.org/tf
- http://wiki.ros.org/tf/Tutorials



ROS geometry_msgs/TransformStamped

- $$\begin{matrix}\text{header.frame\_id[header.stamp]} \\ \text{child\_frame\_id[header.stamp]}\end{matrix}\mathbf{T}$$
- Transform between header (time and reference frame) and child_frame
- 3D Transform representation:
  - geometry_msgs/Transform:
    - Vector3 for translation (position)
    - Quaternion for rotation (orientation)

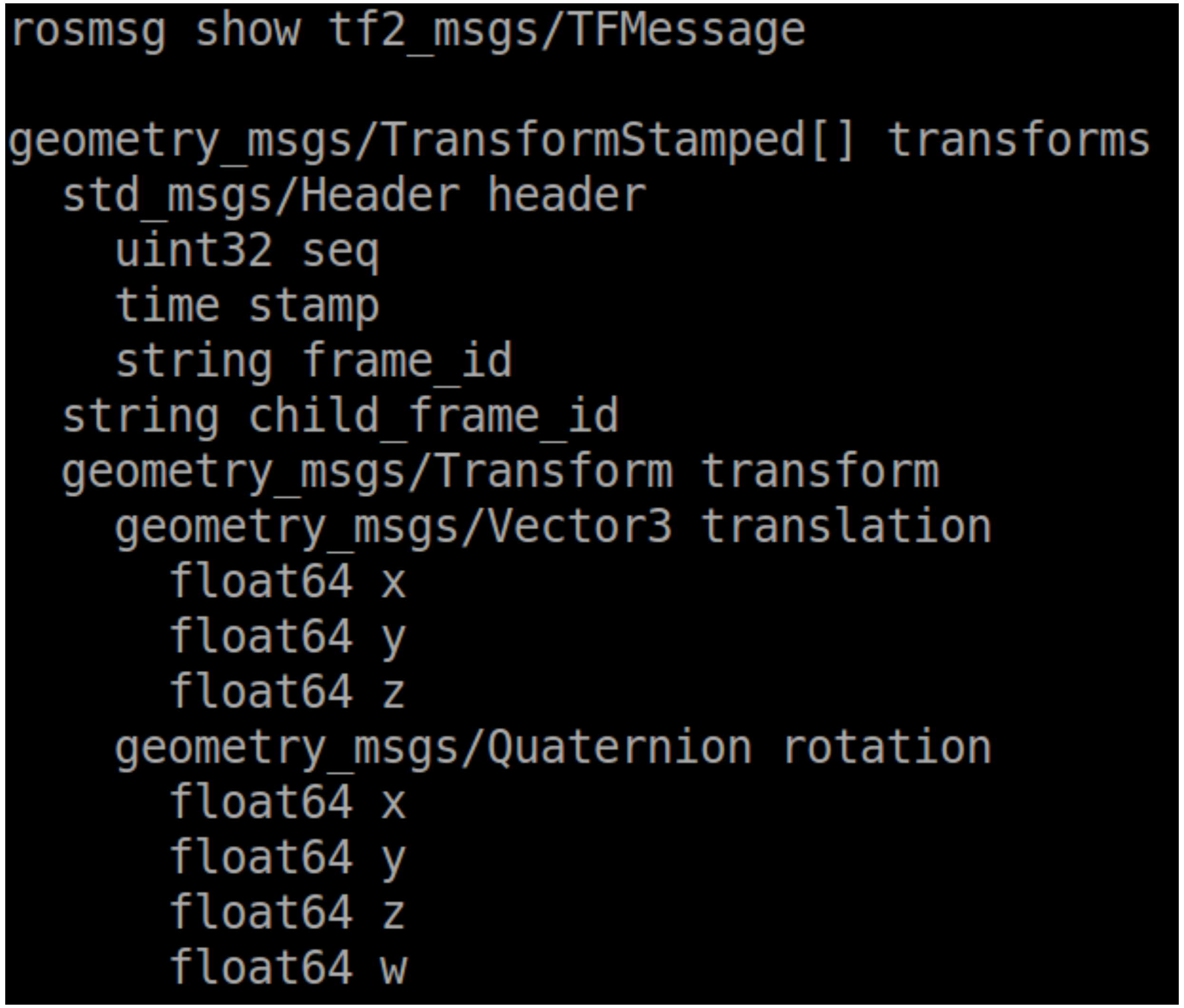


```
rosmsg show geometry_msgs/TransformStamped

std_msgs/Header header
  uint32 seq
  time stamp
  string frame_id
string child_frame_id
geometry_msgs/Transform transform
  geometry_msgs/Vector3 translation
    float64 x
    float64 y
    float64 z
  geometry_msgs/Quaternion rotation
    float64 x
    float64 y
    float64 z
    float64 w
```

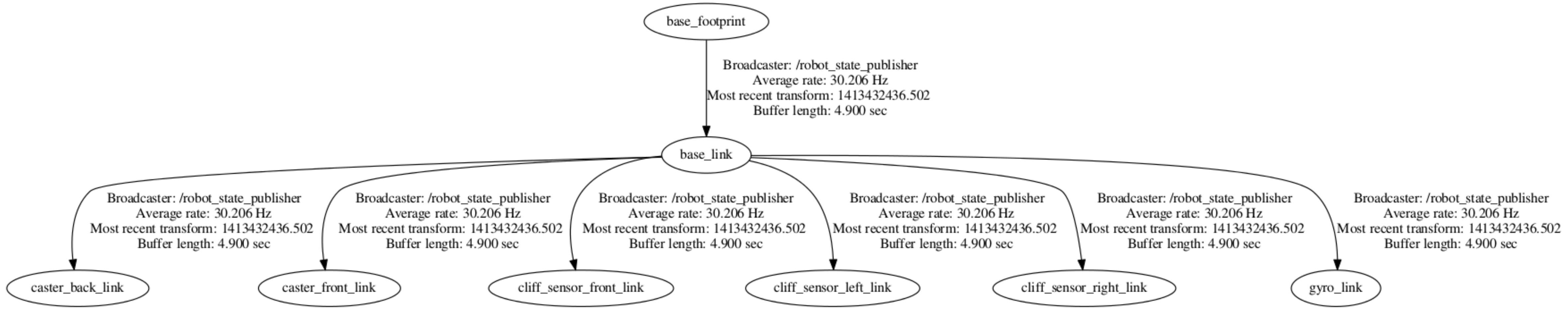
ROS tf2_msgs/TFMessage

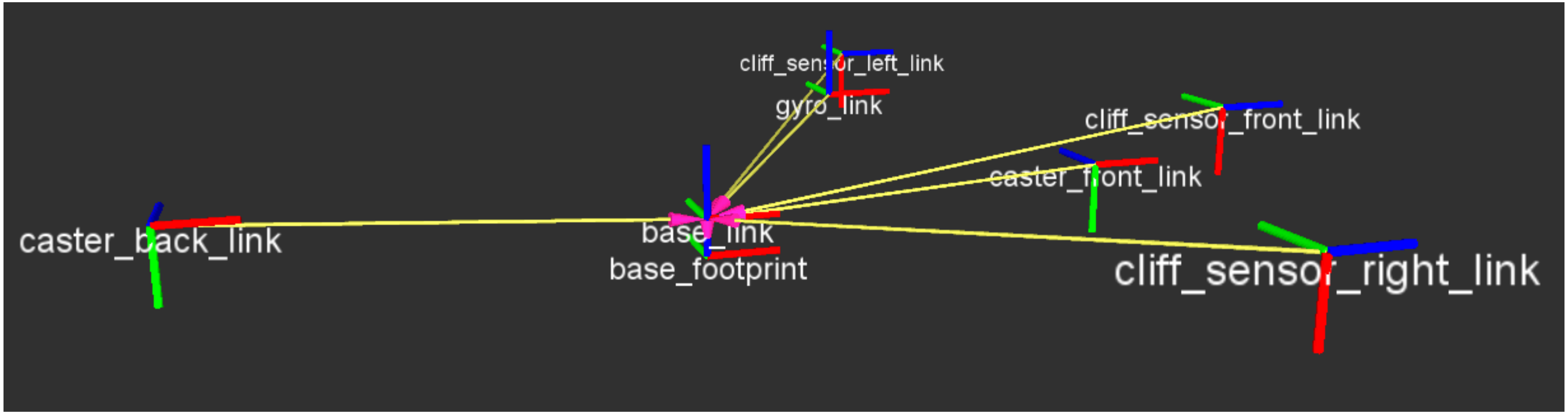
- An array of TransformStamped
- Transforms form a tree
- Transform listener: traverse the tree
  - tf::TransformListener listener;
- Get transform:
  - tf::StampedTransform transform;
  - listener.lookupTransform("/base_link", "/camera1", ros::Time(0), transform);
  - ros::Time(0): get the latest transform
  - Will calculate transform by chaining intermediate transforms, if needed



```
rosmsg show tf2_msgs/TFMessage

geometry_msgs/TransformStamped[] transforms
  std_msgs/Header header
    uint32 seq
    time stamp
    string frame_id
  string child_frame_id
  geometry_msgs/Transform transform
    geometry_msgs/Vector3 translation
      float64 x
      float64 y
      float64 z
    geometry_msgs/Quaternion rotation
      float64 x
      float64 y
      float64 z
      float64 w
```


base_footprint
Broadcaster: /robot_state_publisher
Average rate: 30.206 Hz
Most recent transform: 1413432436.502
Buffer length: 4.900 sec
base_link
caster_back_link
caster_front_link
cliff_sensor_front_link
cliff_sensor_left_link
cliff_sensor_right_link
gyro_link


cliff_sensor_left_link
gyro_link
cliff_sensor_front_link
caster_front_link
caster_back_link
base_link
base_footprint
cliff_sensor_right_link

Transforms in ROS

- Imagine: Object recognition took 3 seconds – it found an object with:
  - tf::Transform object_transform_camera; // ${}^{\mathrm{Cam}[X]}_{Obj}\mathbf{T}$ (has tf::Vector3 and tf::Quaternion)
  - and header with: ros::Time stamp; // Timestamp of the camera image (== X)
    - and std::string frame_id; // Name of the frame (“Cam”)

- Where is the object in the global frame (= odom frame) “odom” ${}^{\mathrm{G}}_{Obj}\mathbf{T}$?
  - tf::StampedTransform object_transform_global; // the resulting frame
  - listener.lookupTransform(child_frame_id, “/odom", header.stamp, object_transform_global);

- TransformListener keeps a history of transforms – by default 10 seconds

ADMIN

Project

- 2 credit points!
- Work in groups, min 2 students, max 3 students!
- Next lecture: Topics will be proposed…
  - You can also do your own topic, but only after approval of Prof. Schwertfeger
    - Prepare a short, written proposal till next Tuesday!

- Topic selection: Next Thursday!
  - One member writes an email for the whole group to Bowen: xubw (at)shanghaitech.edu.cn ; Put the other group members on CC
  - Subject: [Robotics] Group Selection

- One graduate student from my group will co-supervise your project
- Weekly project meetings!

- Oral ”exams” to evaluate the contributions of each member
- No work on project => bad grade of fail

Grading

- Grading scheme is not 100% fixed
- Approximately:

Lecture:	50%	
Quizzes during lecture (reading assignments):		4%
Homework:		18%
Midterm:		8%
Final:		20%
Project:	50%	
Paper Presentation:		5%
Project Proposal:		5%
Intermediate Report:		5%
Weekly project meetings:		10%
Final Report:		10%
Final Demo:		10%
Final Webpage:		5%

Campus Autonomy: ROS2

- Participants: Students from my group

- Port existing ROS1 campus autonomy software to ROS2
- Finish new hardware for campus autonomy robot

- Difficulty: medium
- Requite: good demo & good software
- Supervisor: Prof. Schwertfeger

Campus Autonomy: High Speed Navigation

- Use ROS move_base and TEB planner for high speed robot control.
- Include robot dynamics (mass, acceleration, …)
- Use 3D LRF to detect and predict motion of obstacles (open source software available)
- High-speed navigation through light crowds of students.

- Difficulty: medium
- Requite: good demo
- Supervisor: Prof. Schwertfeger

Mapping Robot: Video Compression

- The new mapping robot has many different sensors -> lots of data
- Especially video data extremely big
- Tasks:
  - Saved ROS 1 bagfile video data in H265 (or better) video format
  - Save meta data in external file (e.g. time stamps)
  - Be able to re-create bagfile from video file and meta data
  - Measure image quality/ image noise to estimate loss!
- Difficulty: Medium
- If work is very good: become co-author of our Dataset Journal paper
- Graduate Supervisor: Bowen Xu

Mapping Robot: Car data collection

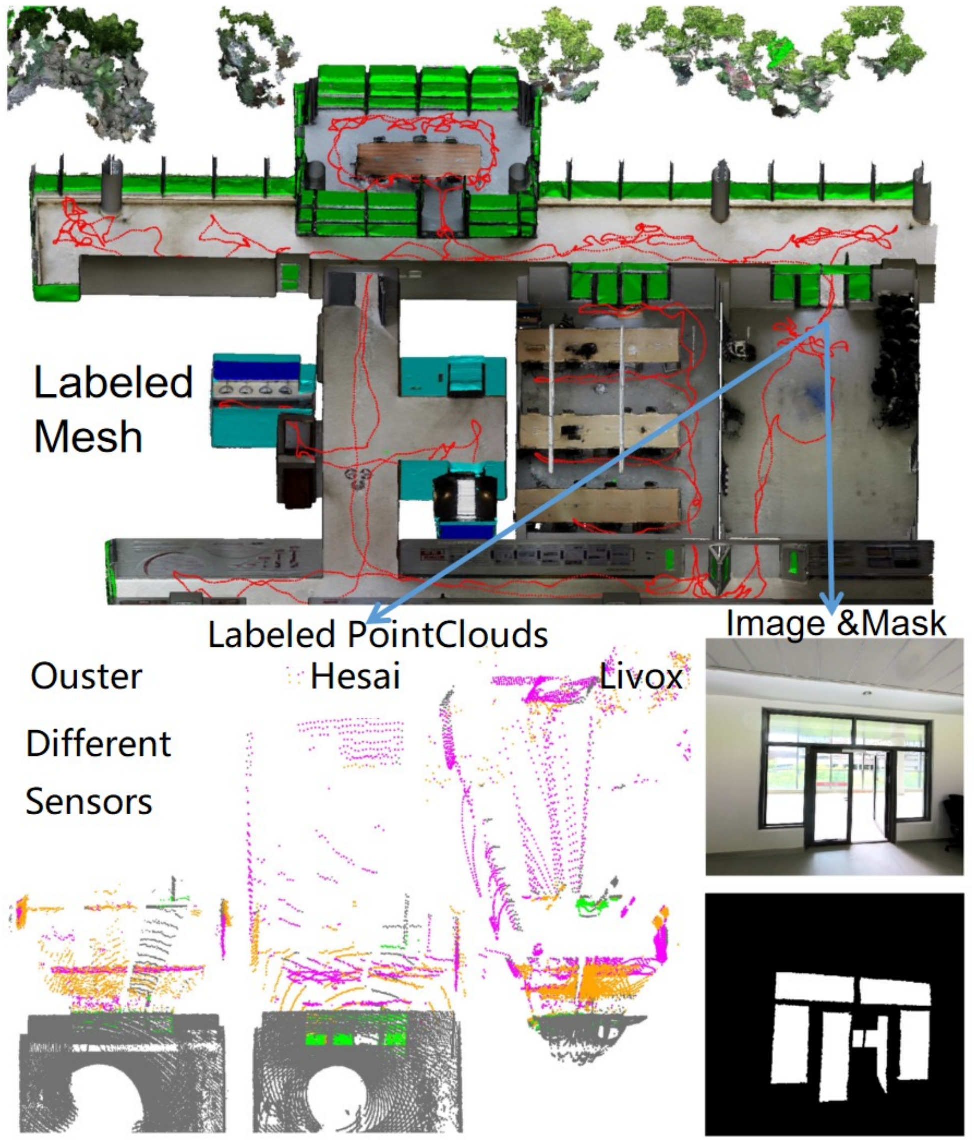
- The new mapping robot is not very fast
- Too slow to map whole campus
- -> strap mapping robot on some small car/ cart
- Move some sensers (e.g. donwlooking cameras) from robot to cart
- Collect dataset of whole campus

- If work is very good: become co-author of our Dataset Journal paper
- Graduate Supervisor: Bowen Xu

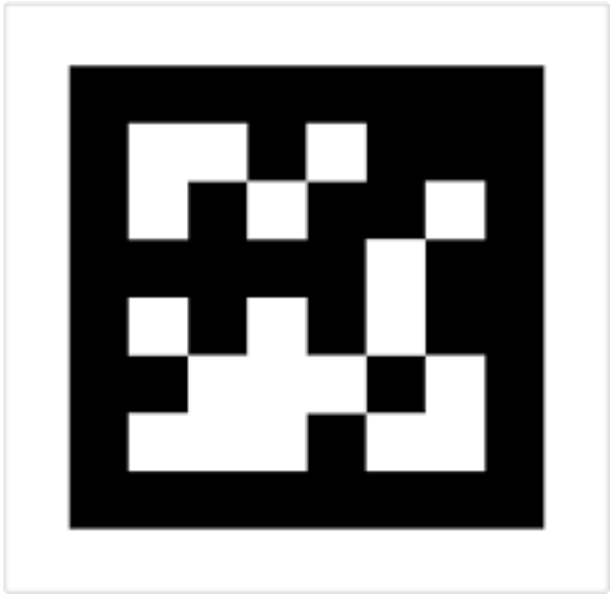
Mapping Robot: Dataset Labelling

- Input: Lidar PointClouds + Pose of the pointcloud
- 1. Use the pointcloud and pose to create mesh
  - ImMesh: An Immediate LiDAR Localization and Meshing Framework
  - SLAMesh: Real-time LiDAR Simultaneous Localization and Meshing
  - Poisson Surface Reconstruction (plugin) – CloudCompare
- 2. Label the mesh with different semantic labels by hand
  - Meshlab
  - Geomagic Warp
  - Cloudcompare
- Label the sensor data use the calibration
  - Open3d + raycasting
  - Opencv
  - PCL
- Dynamic Pointcloud Label
  - Cloudcompare Label
  - Use Open3d/PCL to project to different sensors

- Difficulty: Medium
- If work is very good: become co-author of our Dataset Journal paper
- Graduate Supervisor: Bowen Xu



Mapping Robot: SLAM Evaluation via AprilTags



- Gather ground truth location for Mapping Robot Project
- Print very big AprilTags – and distribute in scenario (e.g. underground parking)
- Use Faro 3D scanner to (semi-) automatically detect and locate AprilTags
- Write a small program to detect AprilTags in the sensor data
- (If observed with more than one camera, minimize error)
- Generate ground truth trajectories with this
- Difficulty: Medium
- Graduate Supervisor: Bowen Xu

Robot Dog Project

- Reserved for certain students
- Program advanced capabilities for robot
- Difficulty: High
- Graduate Supervisor: Xin Duan

LLM Mission planning

- Explore the use of Large Language Models (e.g. GPT 4) for use in mission planning in robotics
- Develop integrated demo for specific task (concentrate on mobile robotics – not manipulation)

- Difficulty: Advanced
- Graduate Supervisor: Fujing Xie

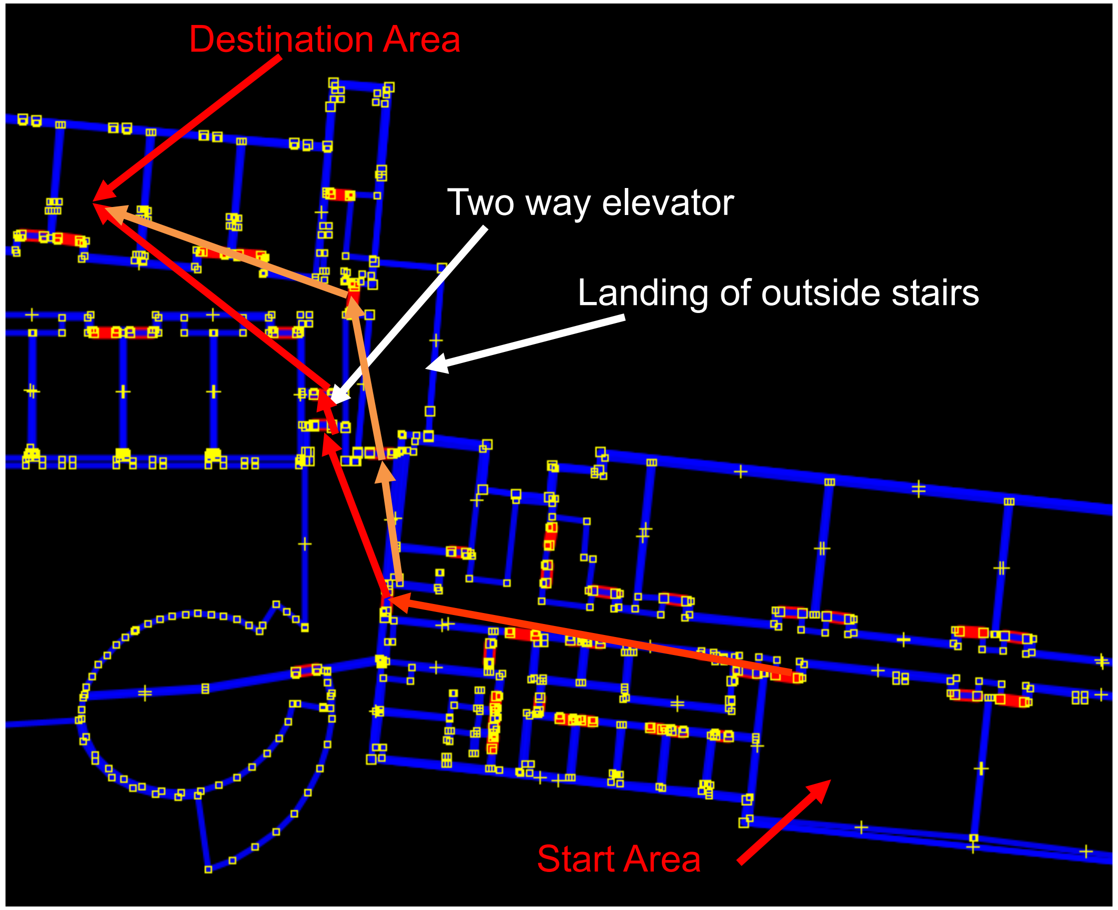
LLM path planning: Align Global path with move_base

- Path planning algorithms should be intelligent to change with respect to environment change, for example
- A robot should avoid outside path during raining
- A robot should avoid a elevator during its maintenance

  You will be given a path planned from a language model, and you need to use this path (ex. ['1d-202', '1d-207', '1d-210', '1d-211']) as global planner in move_base.
- Tasks:

1. Align osmAG map with map used in ROS move_base
2. Given path planned from LLM as global planner, integrate the path to 'BaseGlobalPlanner' of move_base (ref: http://wiki.ros.org/navigation/Tutorials/Writing%20A%20Global%20Path%20Planner%20As%20Plugin%20in%20ROS)
3. Utilize move_base's local planner to navigate through crowd or clutters.
4. Path may change during operation, the local planner needs to provide interface.
5. Provide response to LLM, for example, success or error message

- Difficulty: Advanced
- Graduate Supervisor: Fujing Xie

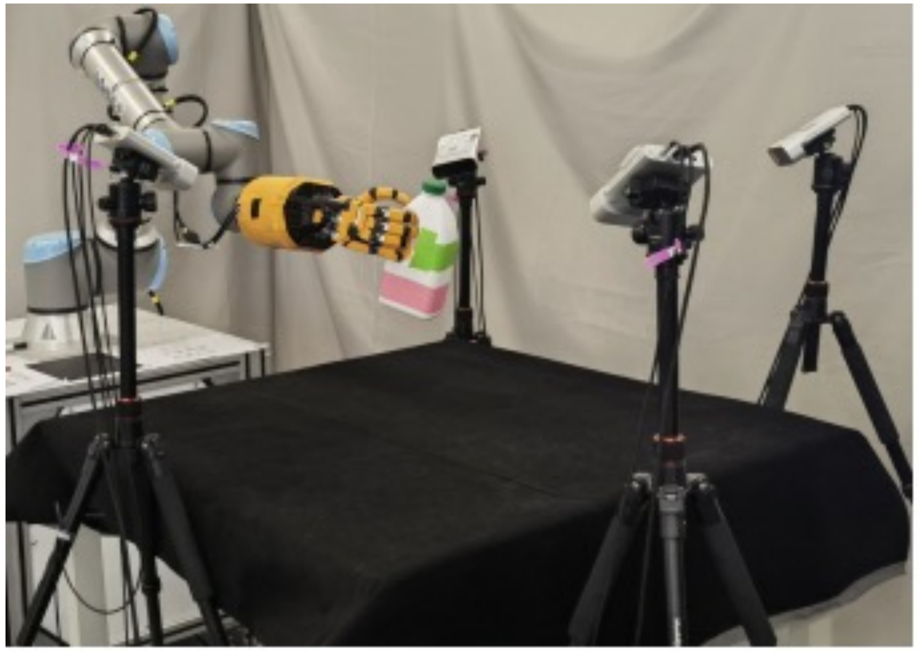


User-friendly Robot Controller: Steamdeck

- Steamdeck:
  - Linux system with touchscreen, joysticks, WiFi, USB-C, etc.
  - Can run ROS and rviz visualization
- Tasks:
  - Install ROS and rviz
  - Program **user-friendly** GUI for Campus Autonomy and Mapping Robot
  - Include 5G teleoperation capabilities
  - Include support for Console control via ssh & keyboard
- Difficulty: Medium +
- Program some GUI with Qt
- Graduate supervisor: Prof. Schwertfeger

Grasping Project cont.

- Paper: RealDex: Towards Human-like Grasping for Robotic Dexterous Hand
- Do follow up work on this paper
- Difficulty: Advanced
- Graduate supervisor: Yang Yaxun
-



Fetch Robot

- Some nice project with fetch robot
- E.g. install ROS2 version of fetch software & program some nice demo
- Difficulty: Advanced
- Supervisor: Yaxun Yang

Robot Writing Project cont.

- Continue more advanced version of robot writing project from Mobile Manipulation 2023
- Include mobile robot action

- Free Space?

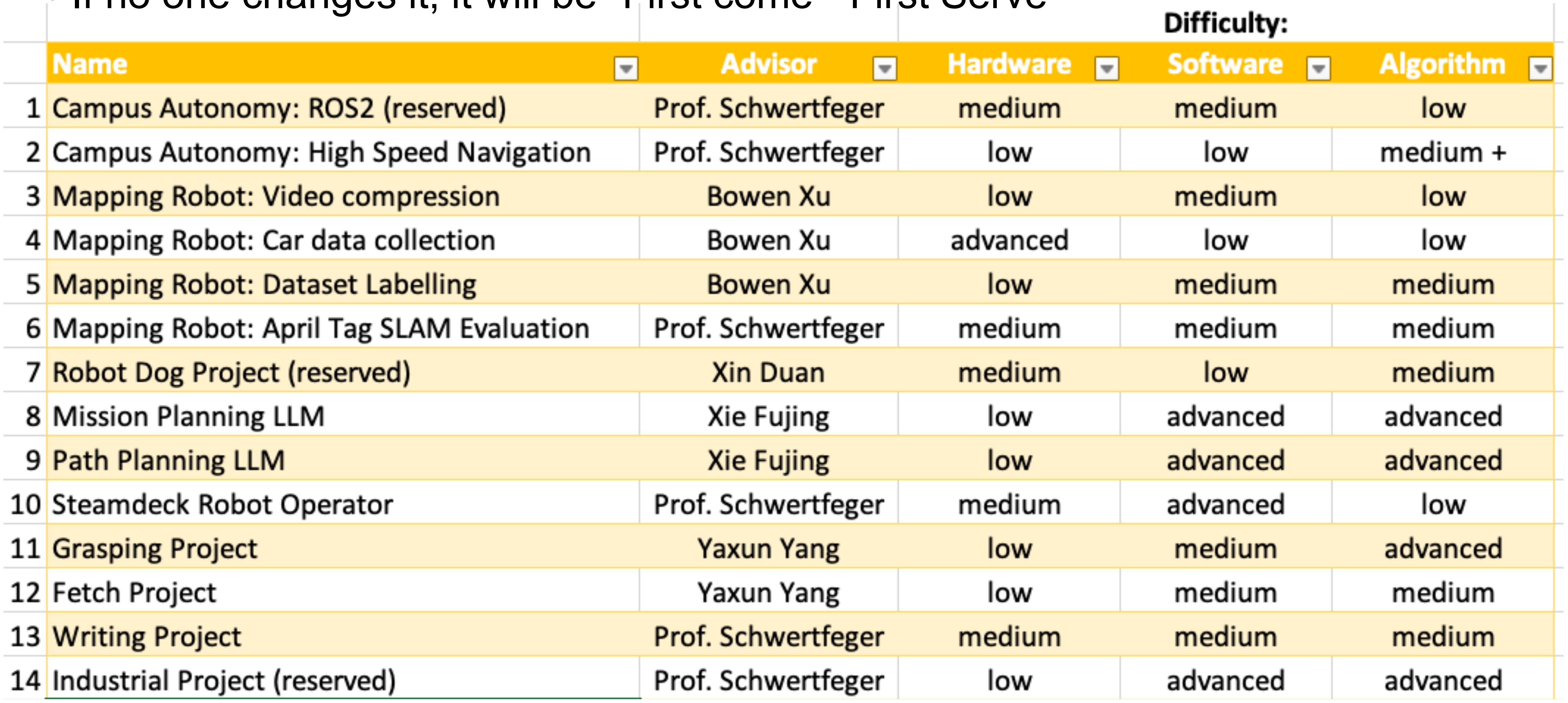
- Difficulty: Advanced
- Supervisor: Prof. Schwertfeger

Industrial Project

- Industrial Robotics Project
- Collaboration project of my group -> reserved for my students

- Difficulty: Advanced
- Supervisor: Prof. Schwertfeger

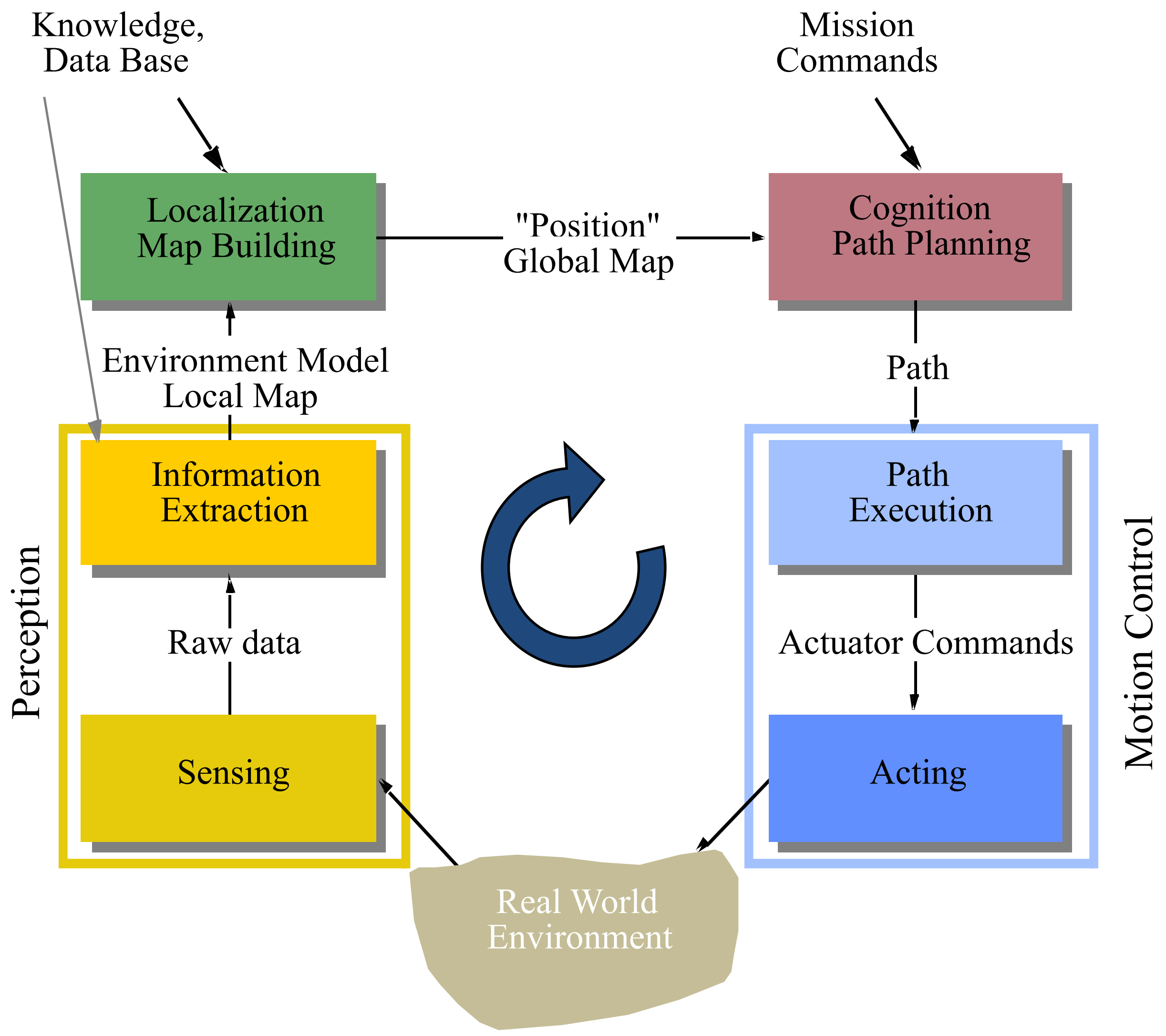
- Max one group per topic!
- In case of double selection we will discuss alternatives with both groups
- If no one changes it, it will be “First come - First Serve”



			Difficulty:		
	Name	**Advisor**	**Hardware**	**Software**	**Algorithm**
1	Campus Autonomy: ROS2 (reserved)	Prof. Schwertfeger	medium	medium	low
2	Campus Autonomy: High Speed Navigation	Prof. Schwertfeger	low	low	medium +
3	Mapping Robot: Video compression	Bowen Xu	low	medium	low
4	Mapping Robot: Car data collection	Bowen Xu	advanced	low	low
5	Mapping Robot: Dataset Labelling	Bowen Xu	low	medium	medium
6	Mapping Robot: April Tag SLAM Evaluation	Prof. Schwertfeger	medium	medium	medium
7	Robot Dog Project (reserved)	Xin Duan	medium	low	medium
8	Mission Planning LLM	Xie Fujing	low	advanced	advanced
9	Path Planning LLM	Xie Fujing	low	advanced	advanced
10	Steamdeck Robot Operator	Prof. Schwertfeger	medium	advanced	low
11	Grasping Project	Yaxun Yang	low	medium	advanced
12	Fetch Project	Yaxun Yang	low	medium	medium
13	Writing Project	Prof. Schwertfeger	medium	medium	medium
14	Industrial Project (reserved)	Prof. Schwertfeger	low	advanced	advanced

HIGH-LEVEL CONTROL SCHEMES

General Control Scheme for Mobile Robot Systems



SENSORS

Introduction to Autonomous Mobile Robots page 102 ff

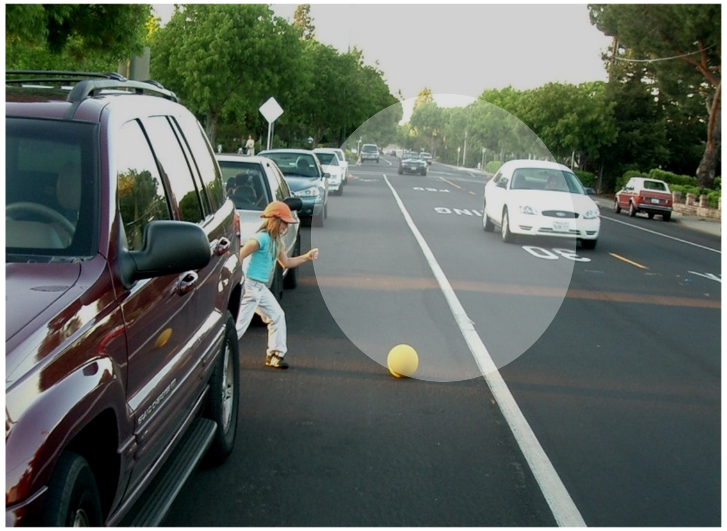
Sensors for Mobile Robots

- Why should a robotics engineer know about sensors?
  - Is the **key technology** for perceiving the environment
  - **Understanding the physical principle** enables appropriate use

- Understanding the physical principle behind sensors enables us:
  - To **properly select** the sensors for a given application
  - To **properly model** the sensor system, e.g. resolution, bandwidth, **uncertainties**

Dealing with Real World Situations

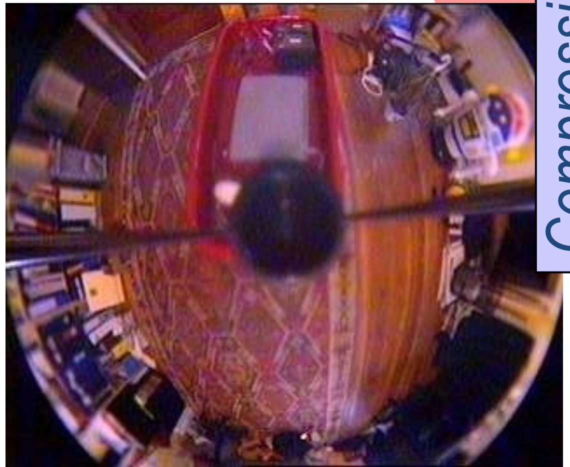
- Reasoning about a situation

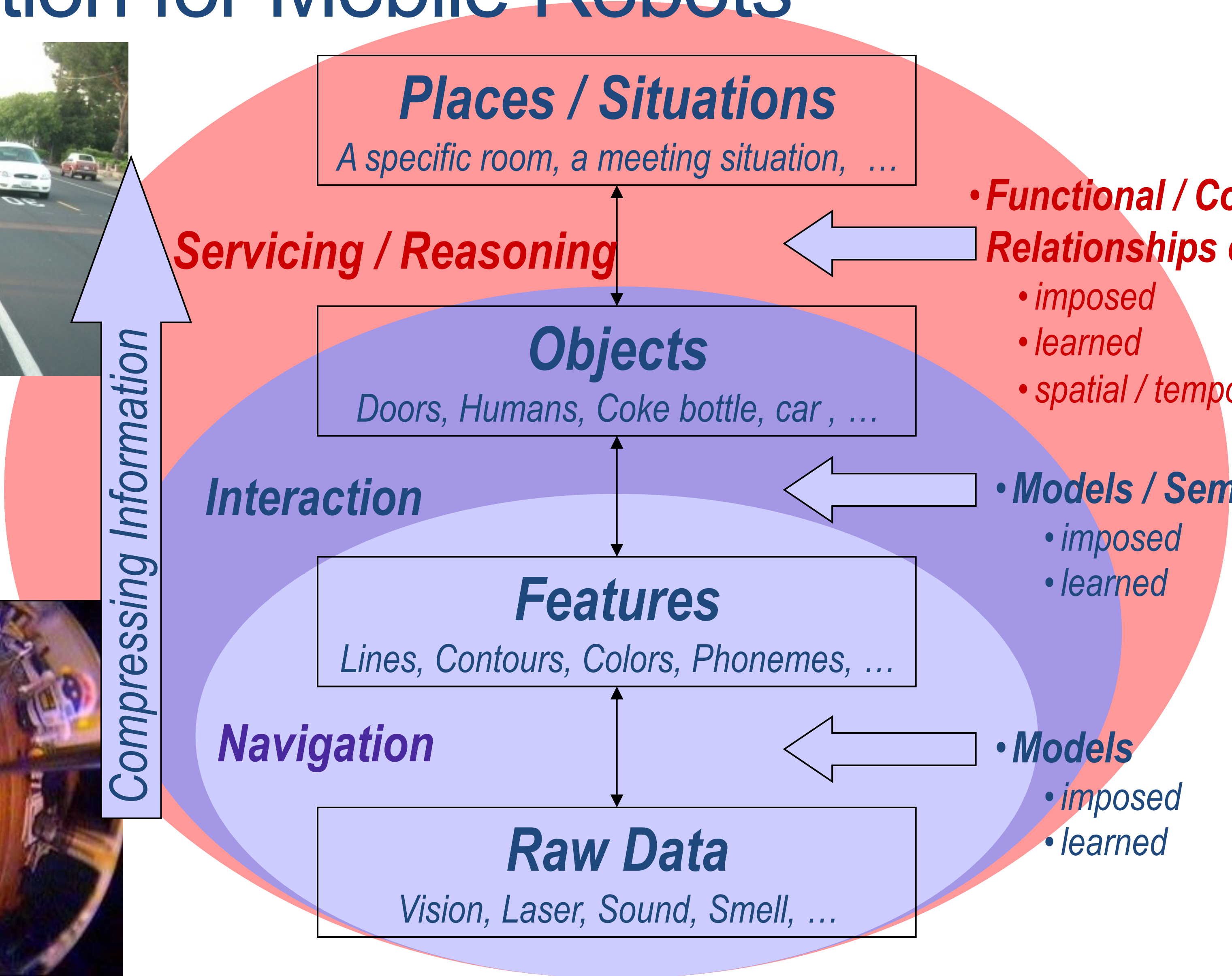


- Cognitive systems have to interpret situations based on uncertain and only partially available information
- The need ways to learn functional and contextual information (semantics / understanding)

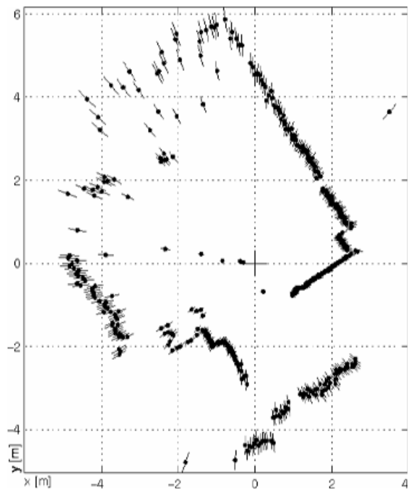
⇒ **Probabilistic Reasoning**

Perception for Mobile Robots



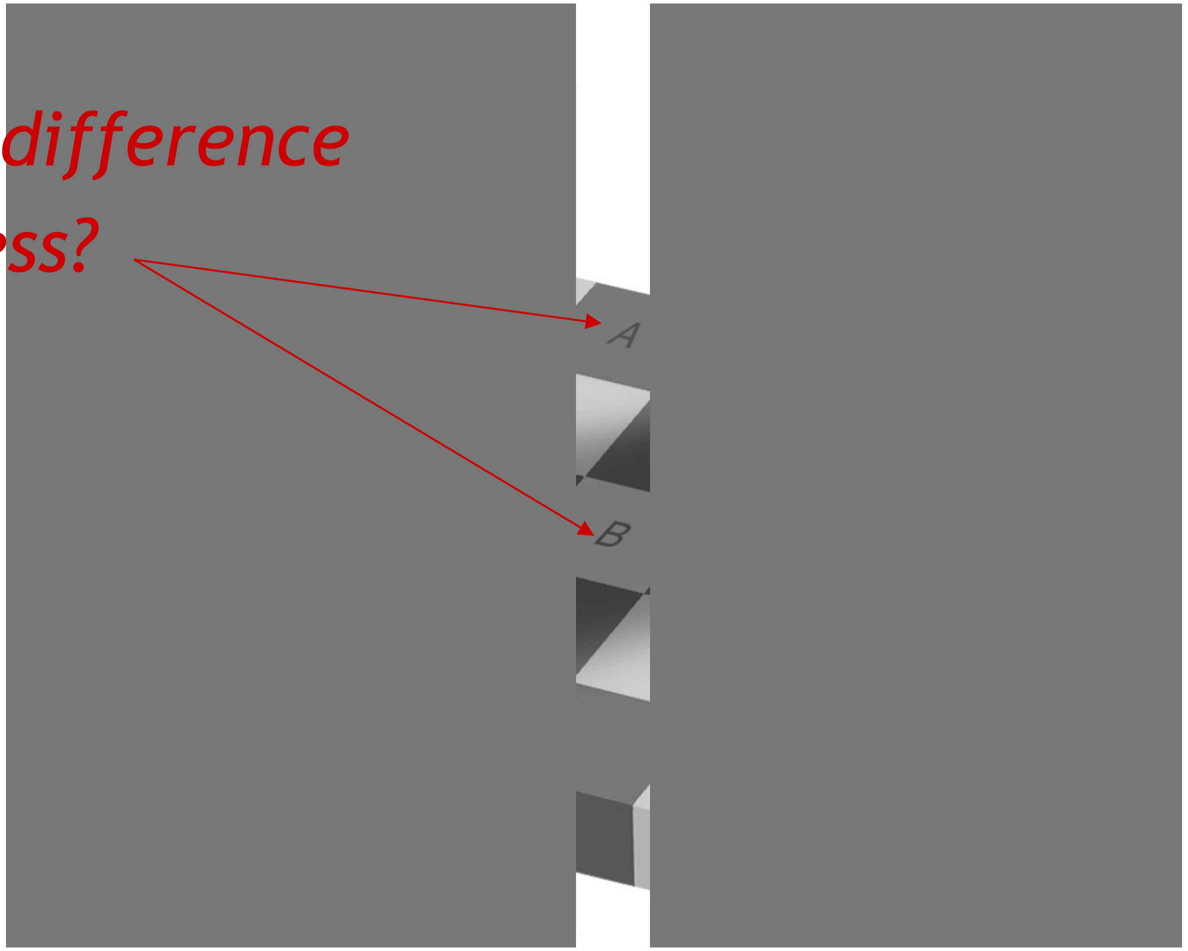

Places / Situations
A specific room, a meeting situation, …
Servicing / Reasoning
Objects
Doors, Humans, Coke bottle, car , …
Interaction
Features
Lines, Contours, Colors, Phonemes, …
Navigation
Raw Data
Vision, Laser, Sound, Smell, …
Compressing Information

- **Functional / Contextual Relationships of Objects**
  - imposed
  - learned
  - spatial / temporal/semantic
- **Models / Semantics**
  - imposed
  - learned
- **Models**
  - imposed
  - learned



The Challenge

- Perception and models are strongly linked



- http://web.mit.edu/persci/people/adelson/checkershadow_downloads.html