



**NANYANG
TECHNOLOGICAL
UNIVERSITY**

School of Mechanical & Aerospace Engineering

Design, Machine, Control, Intelligence

Keynote Speech

Key Technologies for Achieving Autonomous Driving

Ming XIE, PhD (France)

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ABOUT NTU

Vision and Mission



A great global university founded on science and technology, nurturing leaders and creating societal impact through interdisciplinary education and research.

Leadership



Professor Ho Teck Hua

President and Distinguished University Professor



Professor Christian Wolfrum

Deputy President and Provost

Ranked Among the Best in the World



3rd

Nature Index
Young University Rankings



1st

Times Higher Education
Young University Rankings



3rd

US News and World Report
Best Global Universities in Asia



4th

Times Higher Education
Asia University Rankings



15th

QS World University Rankings



4th

QS Asia University Rankings



27th

US News and World Report
Best Global University Rankings



30th

Times Higher Education
World University Rankings



10th

QS World's Most Photogenic Universities

Ranked Among the Best in the World



15-Year Sustainability Manifesto



Solidifying the University's position as a global leader in sustainability

- NTU's sustainability manifesto goals: carbon neutrality by 2035, halve net energy utilisation and new sustainability courses
- First university in the world to launch a sustainability-linked bond with an AAA credit rating from Moody's
- Sustainable campus with eight zero-energy buildings, the most amongst organisations in Singapore
- Home to two of Asia's largest wooden buildings, Gaia and The Wave
- Winner of ISCN's Whole Systems Approach Excellence Award in recognition of sustainable practices in the areas of research, education, community engagement, and infrastructure developments

Main Campus



200 hectares



State-of-the-art-facilities



25 halls of residence

The NTU Smart Campus is a living testbed of tomorrow's technologies and frequently named among the most beautiful campuses in the world.

Medical Campus



School of Medicine

Learning and research

Sports and recreation

Home to the Lee Kong Chian School of Medicine in Novena, Singapore's healthcare district. The school aims to be a model for innovative medical education and a centre for transformative research.

At a Glance



35,400 students

24,800 undergraduates
10,600 postgraduates

8,000

faculty, researchers and
staff from 73 countries

300,900 alumni

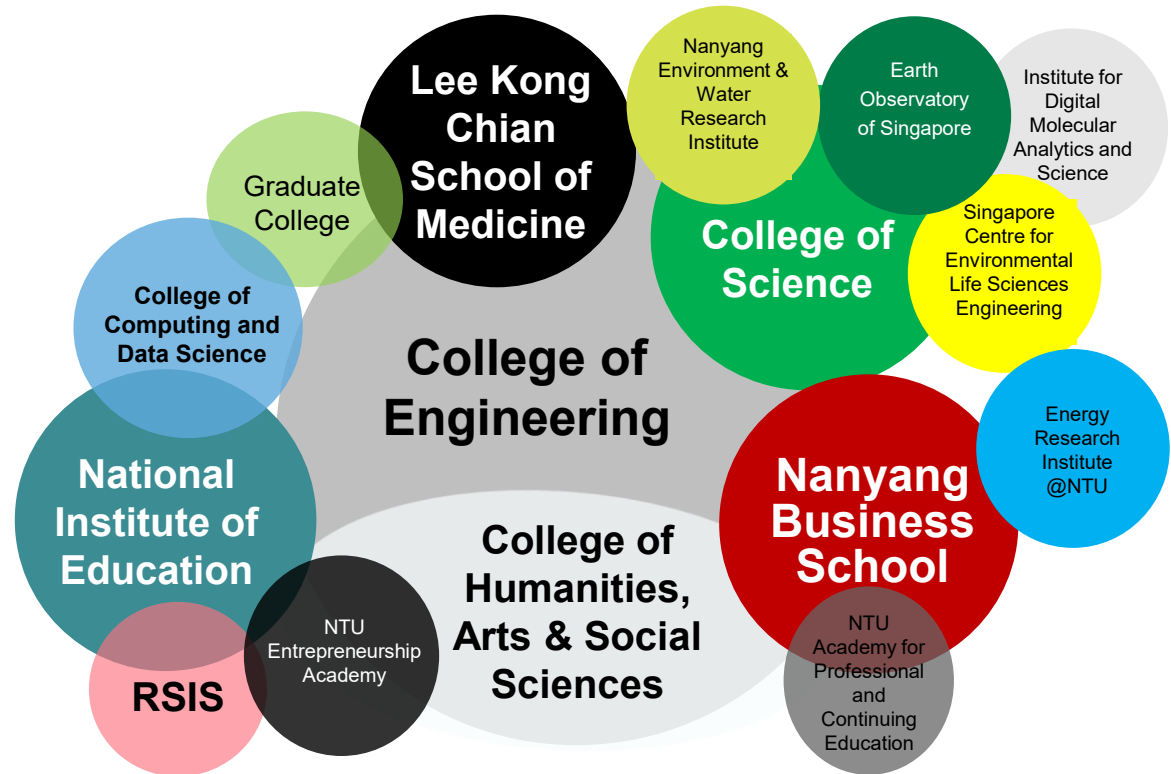
representing 172 nationalities

At a Glance

6
Colleges

15
Schools

**World-class institutes
& research centres**



NTU Academy for Professional and Continuing Education



- Consolidates continuing education and training capabilities and expertise within the University
- Enriches the lifelong learning experience of adult learners, including the University's alumni, making it easier for them to take charge of their own continuing education
- The FlexiMasters programme for continuing education at the Master's degree level, launched in 2020, has grown to more than 35 curricular offerings from all parts of the University

Global Alliance of Industries @ NTU



- Catalysing new university-industry partnerships through multiple consortia, corporate laboratories, multidisciplinary institutes and technology invention disclosures
- Over 250 industry partners and 20 corporate and joint labs with global entities such as Alibaba, Continental, Hewlett-Packard, Nanofilm Technologies, Rolls-Royce and Schaeffler

Top Industry Partners



Top Academic Partners





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Welcome You to NTU

ABOUT SPEAKER



Professor Xie Ming has been:

- Dean/Professor, School of Electrical Engineering and Control Science, Nanjing Tech University, China.
- Guest Professor, Huazhong University of Science and Technology, China.

Professor Xie Ming is now:

- President, Robotics Society of Singapore
- Editor-in-Chief, International Journal of Humanoid Robotics.
- Associate Professor, Nanyang Technological University, Singapore.

Professor Xie Ming has published:

- Three books in English
- Two edited books in English
- Two books in Chinese
- Over 40 International Journal Papers
- Over 100 International Conference Papers

Professor Xie Ming has received many awards and over 10 granted patents.

Ming XIE

Associate Professor (1999 - present)

<http://personal.ntu.edu.sg/mmxie>

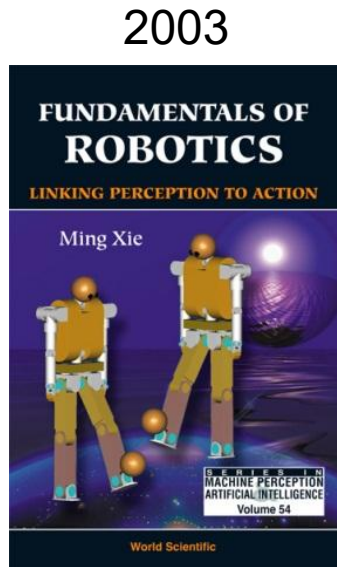


1984: B.Eng (China)

1986: Msc (France)

1989: Ph.D (France)

Recipient of
Chinese Government's
Overseas Scholarship
(1984 - 1989)



Knowledge
Innovation



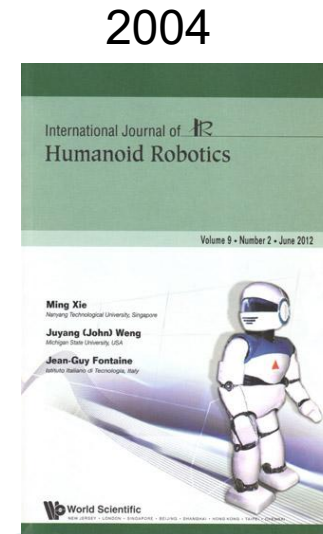
Technology
Innovation

Product
Innovation

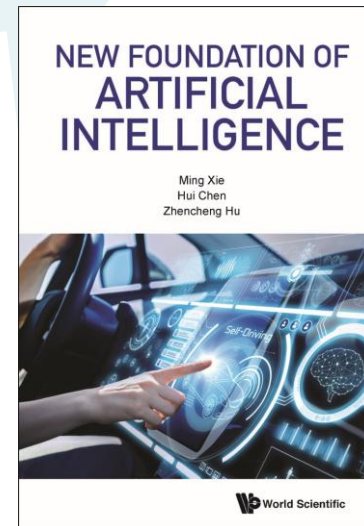
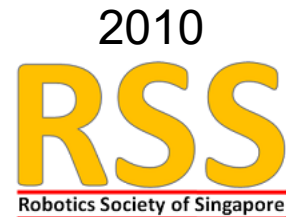
(Robot Driver)
(Robot Worker)

Teaching Portfolio

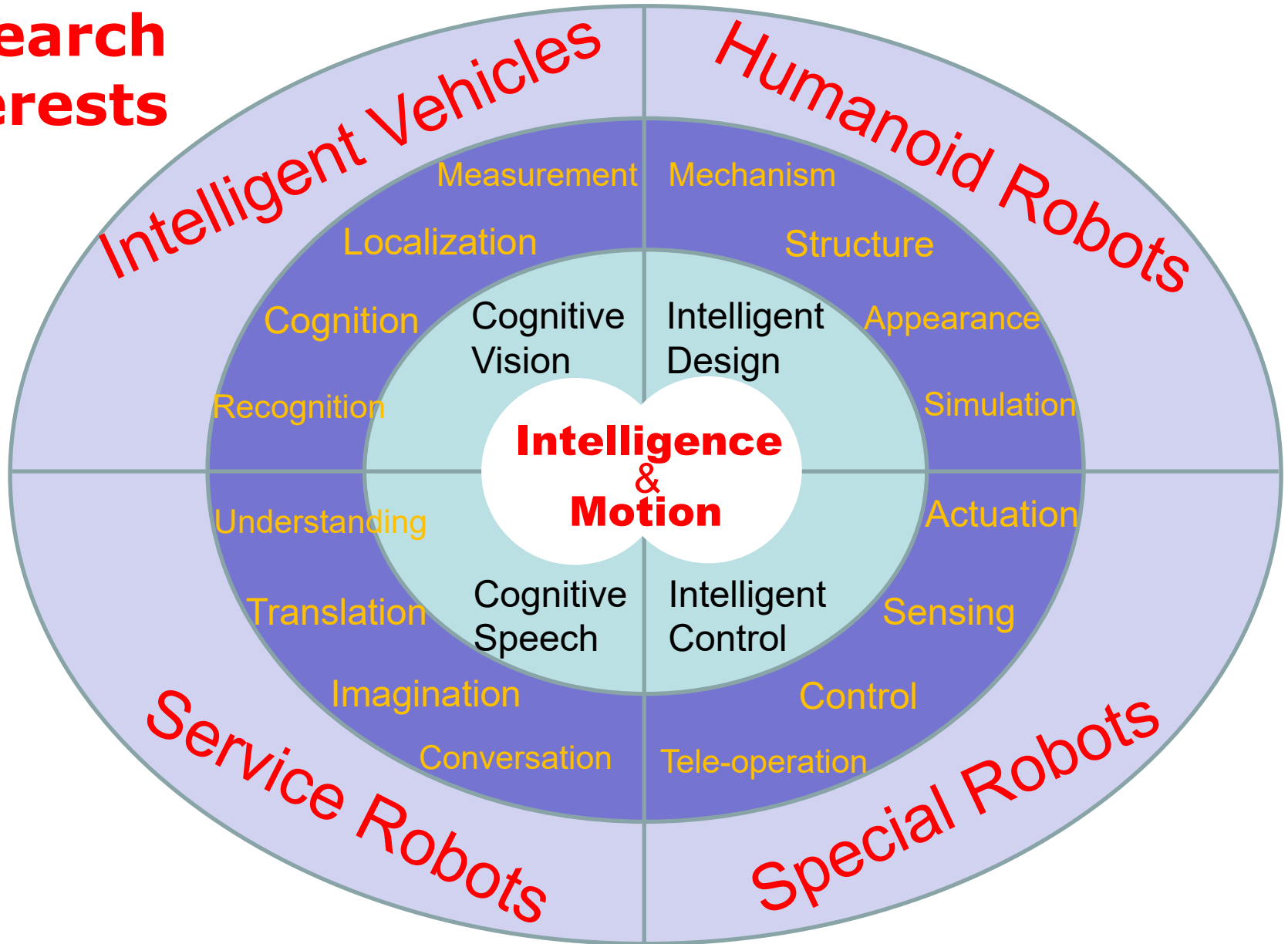
1. Sensors
2. Robotics
3. Microprocessors
4. Machine Intelligence



Social
Service



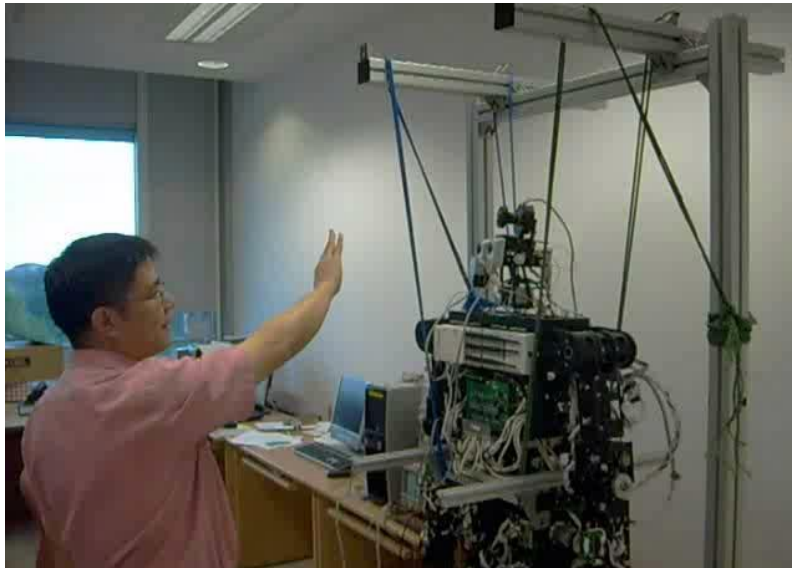
Research Interests



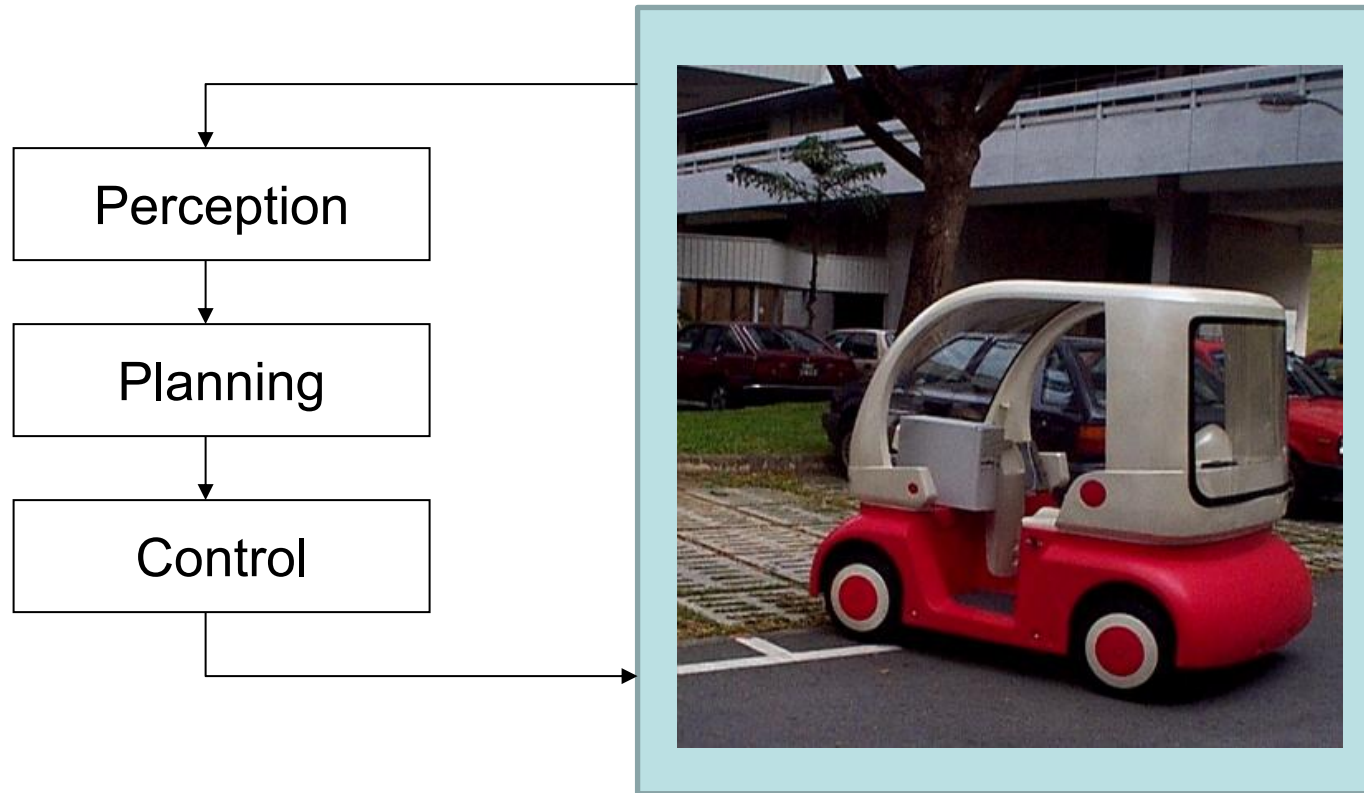
Nanyang Technological University



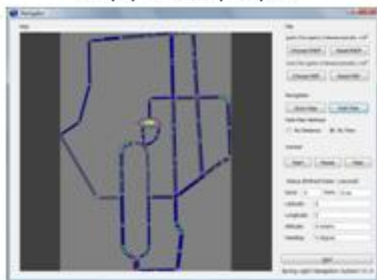
Some Demonstrations ...



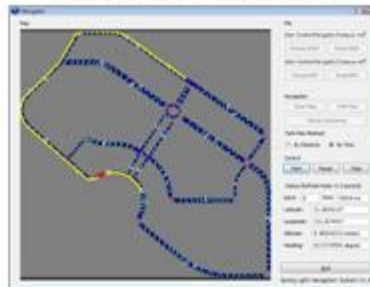
Autonomous Land Vehicle ...



汽车卫星定位



汽车定位及路径规划



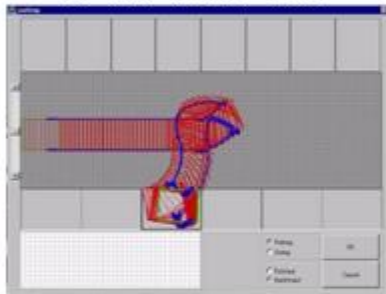
车道线自动识别



车道线自动跟踪



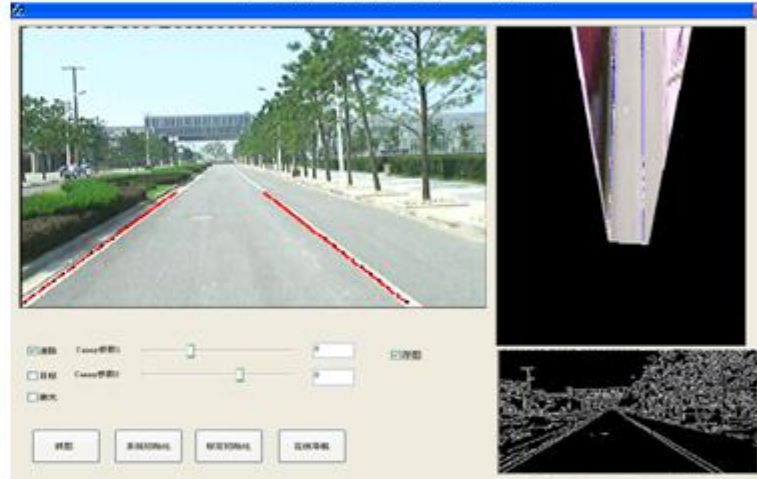
汽车自动泊车仿真



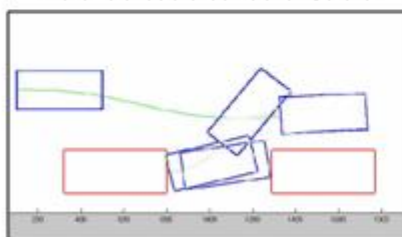
汽车自动串行泊车



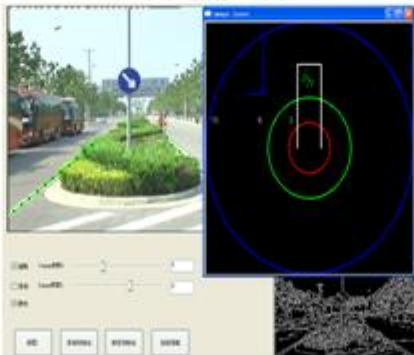
汽车自动保持车道行驶



汽车自动并行泊车仿真



汽车激光测距



汽车自动保持车距行驶

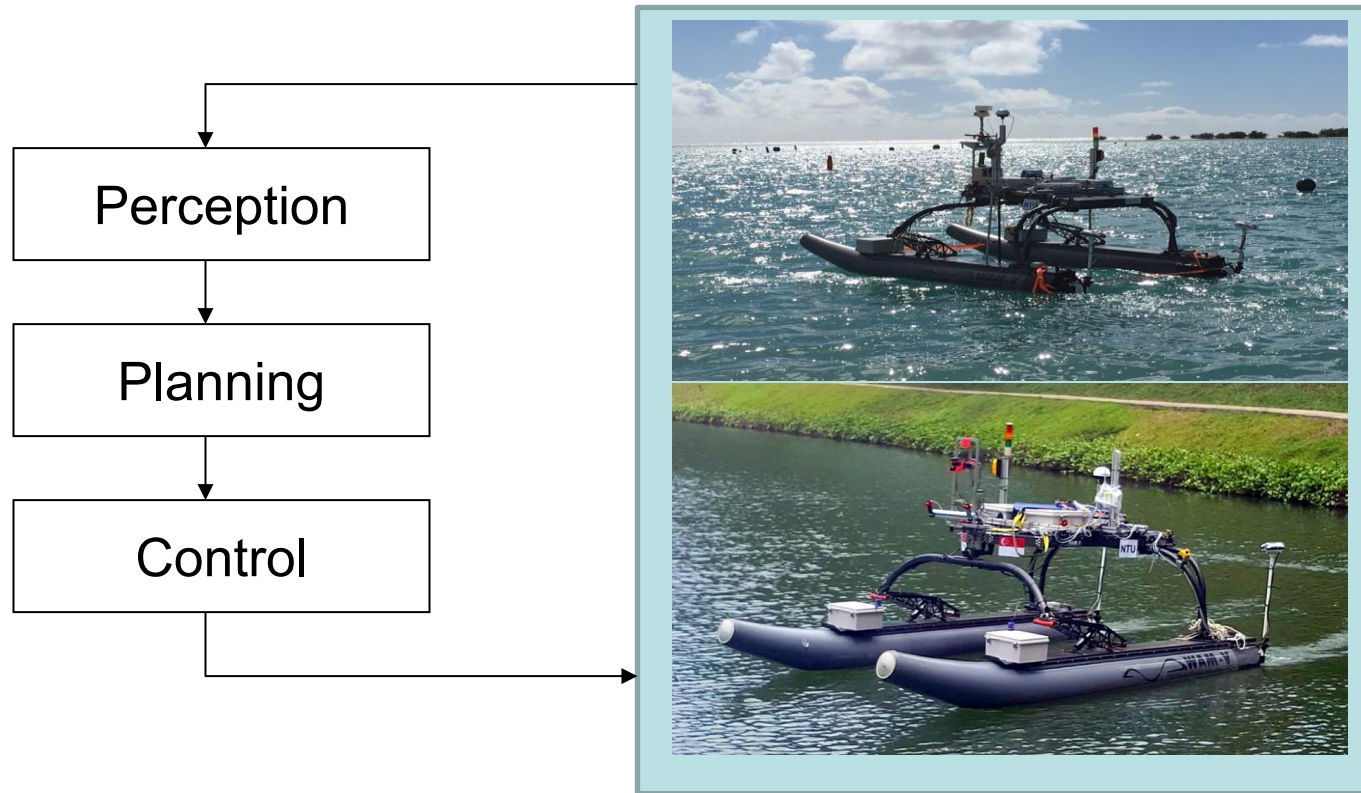


Nanyang Technological University



(Learning, Teaching) <o> (Research, Innovation) <o> (Leadership, Service)

Autonomous Surface Vehicle ...



WARM UP QUESTIONS ...

Warm-up Question 1

- Which one of the following two terminologies is a synonym for Artificial Intelligence?
 - A) Artificial Brain 人工大脑
 - B) Artificial Mind 人工识体



Warm-up Question 2

- Which one of the following four terminologies is a synonym for Learning?
 - A) Cognition
 - B) Optimization
 - C) Tuning
 - D) Calibration

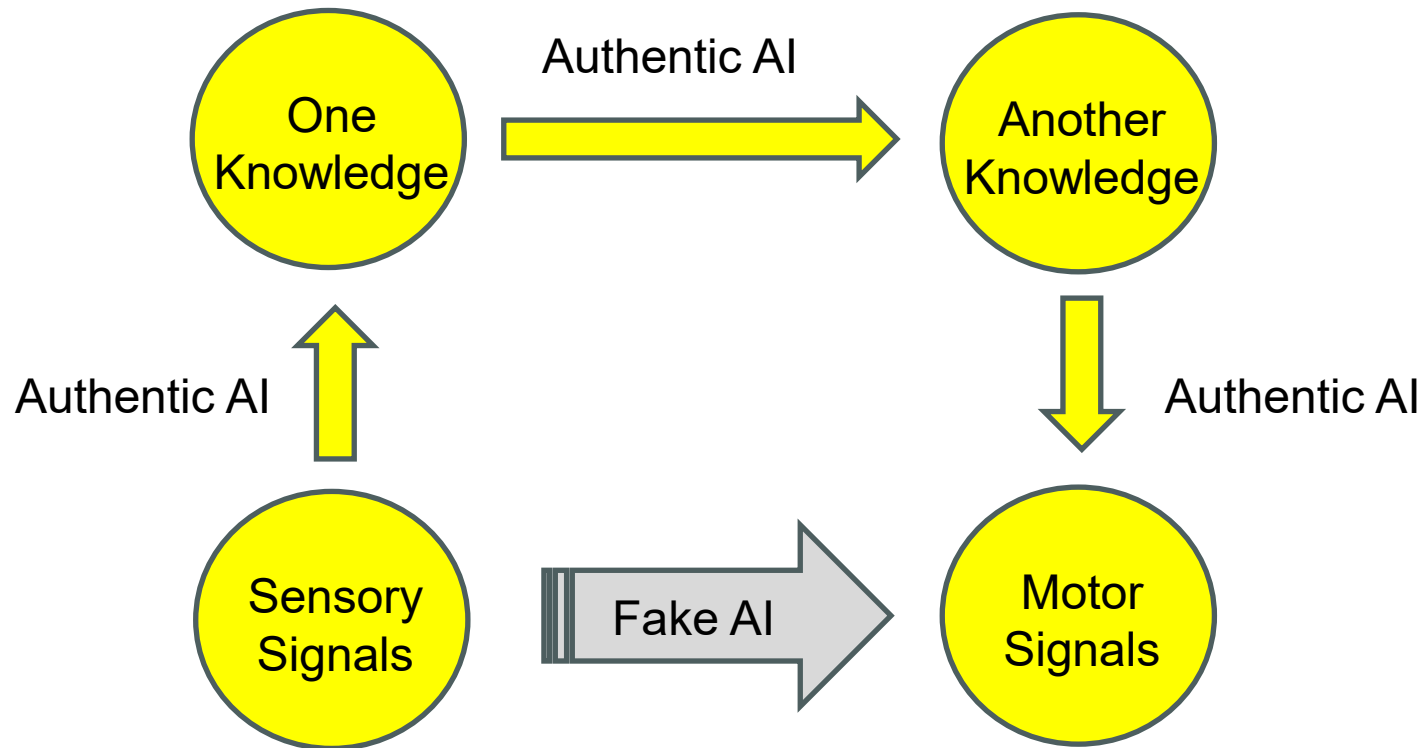


Warm-up Question 3

- Which one of the following four transformations is not a process of Authentic AI?
 - A) Signal to Signal
 - B) Signal to Knowledge
 - C) Knowledge to Knowledge
 - D) Knowledge to Signal

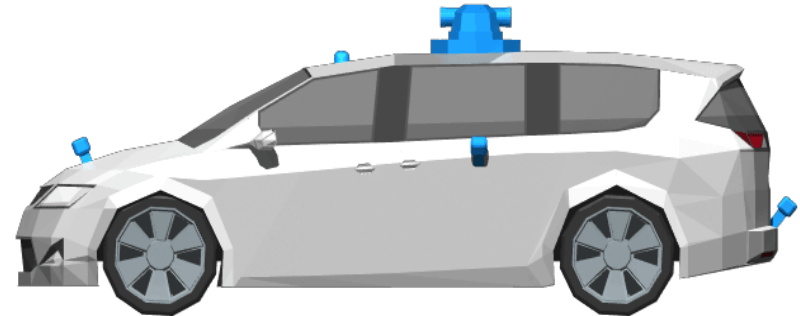


Authentic AI versus Fake AI



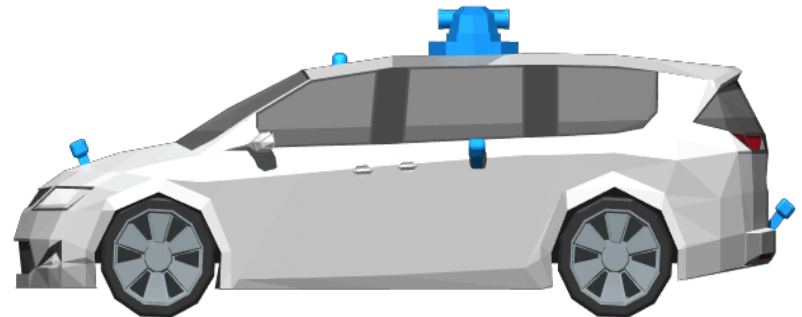
Key Takeaways: You will know ...

- Major Initiatives
 - Autonomous Land Surface Vehicles
 - Autonomous Water Surface Vehicles
- Key Technologies of Autonomous Driving
 - Perception
 - Planning
 - Control
- Roadmap Toward Vehicle's Self-Intelligence



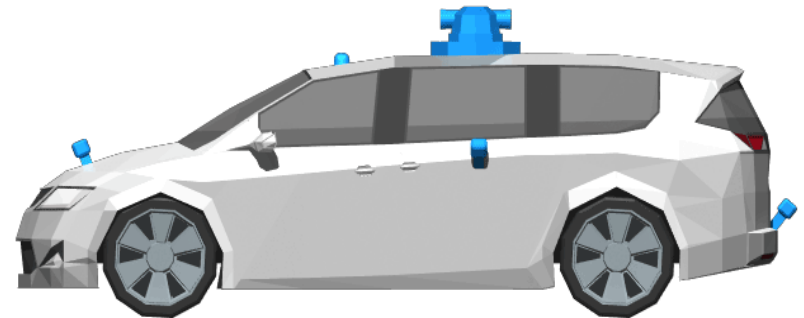
Outline of Today's Talk

- Why to Develop Autonomous Vehicles?
- What is an Autonomous Vehicle?
- What are the Major Initiatives?
- How to Develop Autonomous Vehicles?
 - Key Technologies of Perception
 - Key Technologies of Planning
 - Key Technologies of Control
- Future Works



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Transportation is one of the four basic necessities in our daily life ...

- Transportation provides us with:

- Speed

- Comfort

- Safety

- Affordability



Transportation also causes a lot of problems to our societies ...

- Traffic Jams
- Traffic Accidents
- Air Pollution
- Cost of Ownership
- Space for Parking





日本名贵跑车连环相撞 500多万元瞬间报销

2011.12.9
(东京法新电)日本发生相信是历来最昂贵的撞车事故,包括8辆法拉利和一辆蓝宝基尼在内的14辆汽车,在一条高速公路上连环相撞。这些汽车的总价值达400万美元(约512万新元)。

连环车祸发生在本州“中国快车道”(Chugoku Expressway)的东向车道上。目击者说,车祸是因一辆超速汽车在湿滑的路面上失控引发的。从车祸现场可见多辆鲜红色法拉利(Ferrari)已变成一堆堆废铁,汽车残骸分布在400公尺长的路段上。

警方说,由大约20辆豪华车组成的车队,星期天上午在湿滑的高速公路上行驶,不料领头的法拉利突然失控撞向护栏。尽管后面的车猛踩刹车,但还是太迟了。

高速公路巡警神谷说:“我从来没有看过这种景象。法拉利很少成群行驶。”他说,有5男5女在车祸中受轻伤。“他们很可能是双双对对坐在车上。”



Japan

Eight Ferrari + One Lamborghini + Five Other Cars

包括法拉利和蓝宝基尼在内的多辆名贵跑车,在日本一条高速公路上撞毁。(法新社)

神谷说,这个车队可能是要到130公里外的广岛参加超级车聚会。他补充说:“超速可能是肇事原因,但我们还在确认车祸起因。”

涉及连环车祸的还有另一辆丰田普锐斯环保车和另一辆丰田汽车,但相信

两辆车都不是豪华车车队的成员。另外3辆涉案汽车则都是马赛地。

一位目击者说:“车队的时速达到140至160公里,其中一辆失控旋转,然后全部就撞成一团。”出事路段的车速限制是每小时80公里。

据说涉案的其中一辆法拉利是F430 Scuderia,该车型的时速可达320公里。

日本媒体说,车祸的总损失金额可能达3亿日元(约380万美元、487万新元)。一辆崭新法拉利的零售价是2000

多万日元,蓝宝基尼(Lamborghini)零售价则可达3000万日元。

日本媒体说,日本的超级车车主不一定是有钱人,许多可能是用上所有积蓄来满足驾驶名牌车美梦的年轻人。

Improvements?

- Zero Pollution
- Zero Accident
- Zero Ownership



Robot Taxi



Autonomous Vehicles



巴黎推出电动车共享计划

2011.12.6



巴黎周一开始实施电动车共享计划，推出250辆车供参与者使用。（路透社）

（巴黎美联社）法国首都巴黎志在成为未来城市的创新者，最新推出了电动汽车共享计划，希望减少这座城市的空气和噪音污染。

和其他城市相比，巴黎推出的电动车计划规模最大：250辆电动汽车已在周一上路，预计到明年夏天将推出2000辆，未来两年内计划达到3000辆。

巴黎此前成功推行脚踏车租赁计划，当局在这基础上推出奥托利（autoLib）计划。巴黎官员希望，前天推出的这一电动车共享计划，能像埃菲尔铁塔和圣母院一样，成为巴黎生活的一部分。

汽车的锂金属聚合物电池，汽车充电一次可以行驶250公里。

多城奥托利参与计划负责人马蒂说：“该计划的首要目的是对抗空气污染，这些汽车不会排出二氧化碳和废气，也不会产生噪音。研究显示，对城市的第一干扰就是噪音。”

虽然许多世界级大城市都在发展减少碳排放的环保汽车，但是巴黎表示，他们的计划规模最大：250辆电动汽车已在周一上路，预计到明年夏天将推出2000辆，未来两年内计划达到3000辆。

参与者只需出示身份证、驾照和信用卡，就可以通过互联网与客户服务代表签约。当局总共在巴黎及其周边城镇，设立了40座特别的玻璃汽车棚，这些客户服务代表就在其中办公。

奥托利计划还帮电动车制造商和使用者一个大忙，那就是解决了巴黎充电站不够用的问题。电动汽车的主人只要每年交180欧元，就可以在奥托利充电站给自己的车辆“加油”。

奥托利（autoLib）计划采用的是四座小型汽车，是意大利汽车设计师宾尼法利纳和法国波洛莱集团合作的产物，驱动

参与费是一天10欧元（约17新元）、一周15欧元和一年144欧元。另外，根据不同的租赁计划，每小时的用车费从4欧元至9欧元不等，车辆损坏时用户要另外付费。

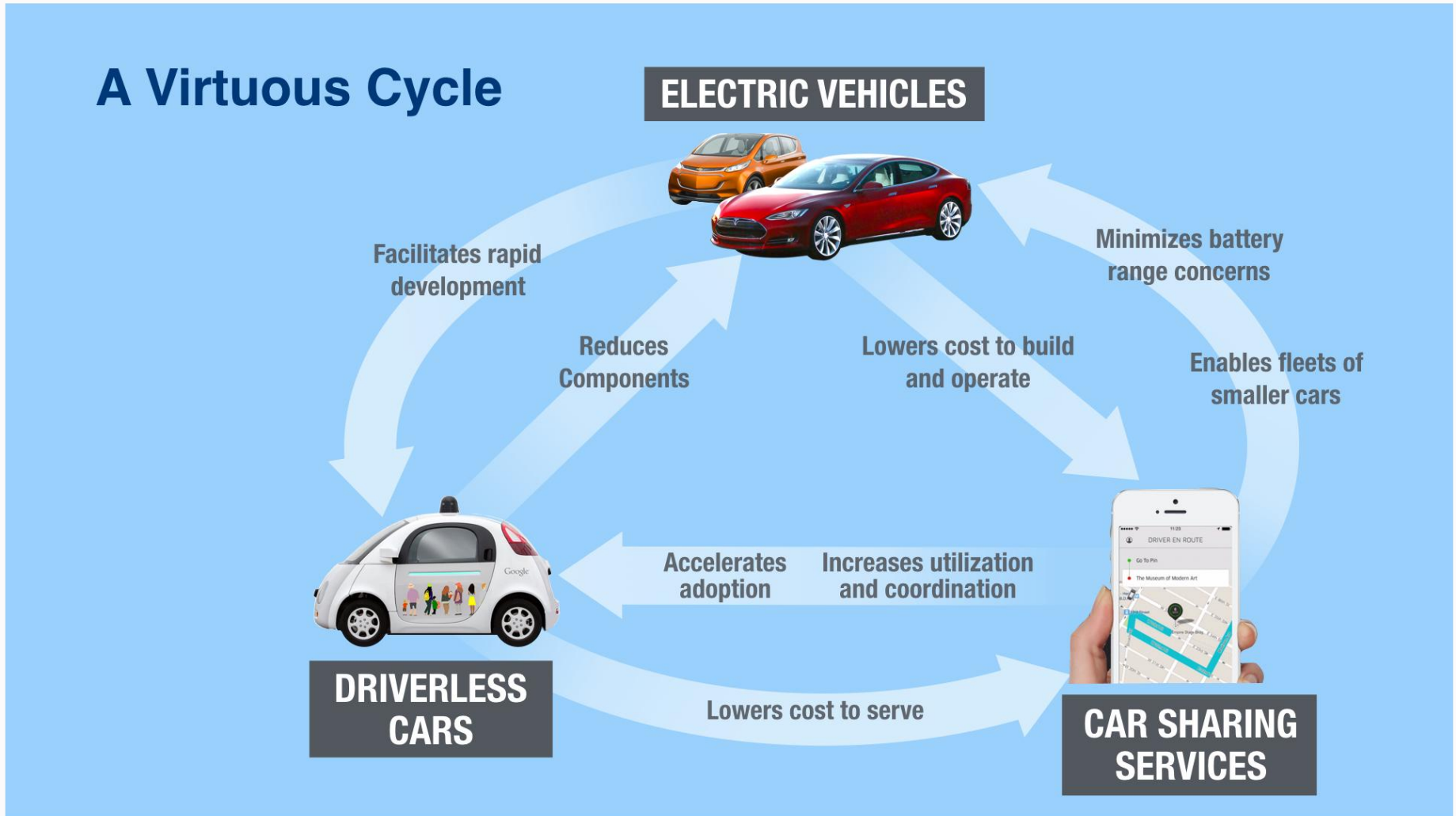
马蒂还说，已经有大约2000人登记为奥托利用户，另外还有像中国广州或巴西的里约热内卢这样城市的官员，前往巴黎观看计划实施的情况。



Zero Accident ...

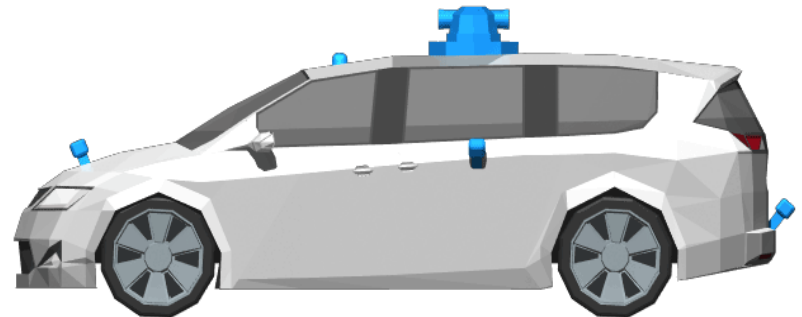


Car Sharing ... (Zero Ownership)

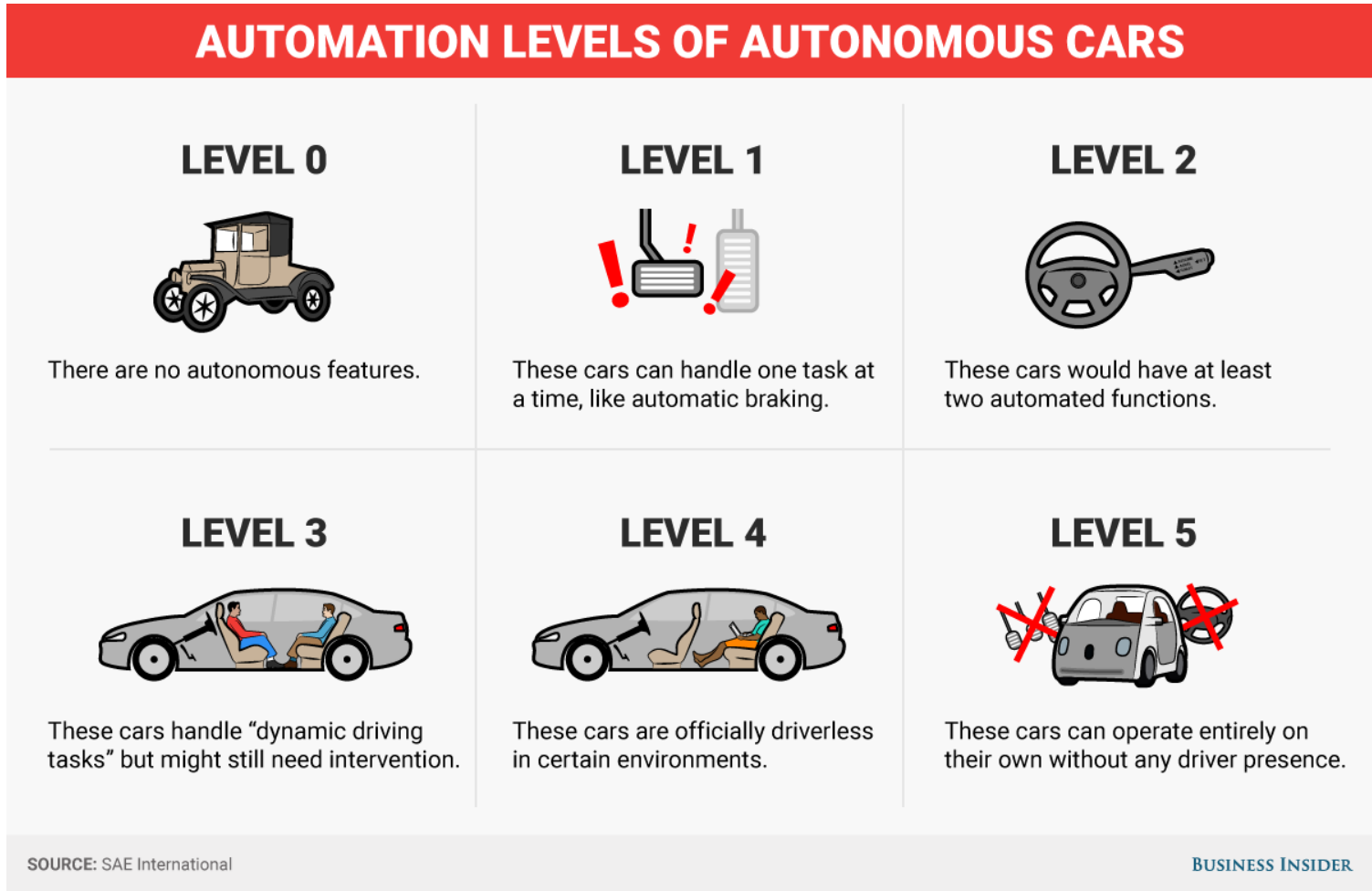


Outline of Today's Talk

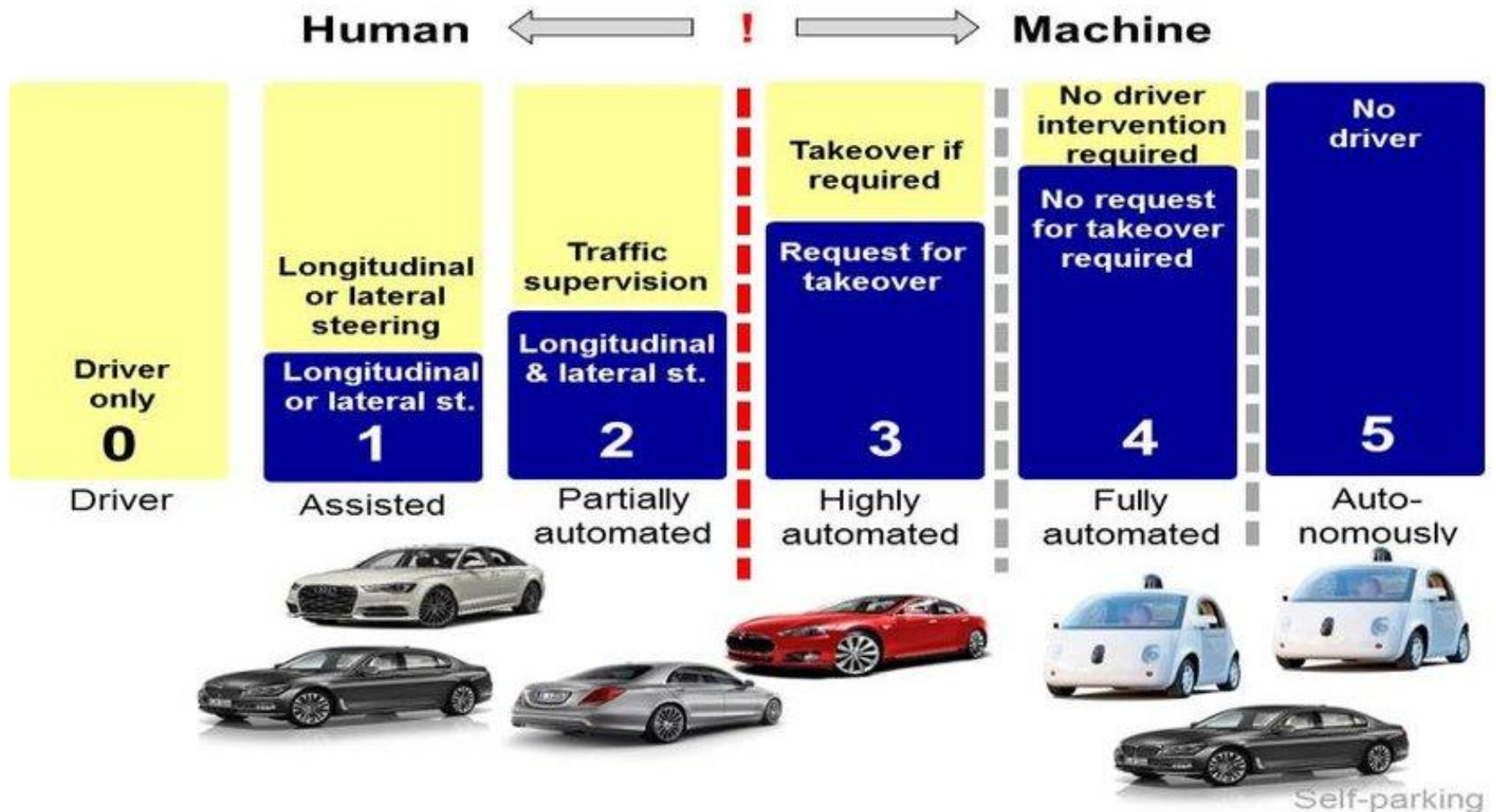
- Why to Develop Autonomous Vehicles?
- What is an Autonomous Vehicle?
- What are the Major Initiatives?
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**What is an autonomous vehicle? Technology-centric Answer:
An autonomous vehicle is the outcome of transition from partial automation to full automation.**



**What is an autonomous vehicle? Developer-centric Answer:
An autonomous vehicle is the outcome of transition from human driver to machine driver.**



**What is an autonomous vehicle? Buyer-centric Answer:
An autonomous vehicle is the outcome of transition from partial autonomy to full autonomy.**

- Velocity Control (Cruising)
- Steering Control
- } In all situations
- } Level 1

- Trajectory Following
- Target Following
- } In all situations
- } Level 2

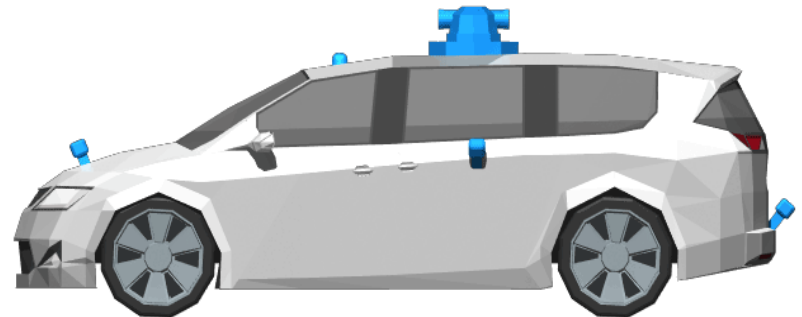
- Collision Avoidance
- } In all situations
- } Level 3

- Lane Changing
- Takeover
- } In all situations
- } Level 4

- Sequential Parking
- Parallel Parking
- } In all situations
- } Level 5

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History of Autonomous Vehicles (1939 – 2017)

The world's largest Eureka-PROMETHEUS Project is missing ...

Initiative on Autonomous (Water) Surface Vehicles is missing ...

1939

General Motors presents the concept of a driverless car at the 1939 World's Fair.



1998

Mercedes, Toyota and Mitsubishi begin offering adaptive cruise control.



2012

Google begins testing self-driving models on public roads.



2016

Uber, Delphi and NuTonomy begin testing robot taxis in Pittsburgh and Singapore.



2017-21

Google promises to introduce the first fully autonomous car, while Ford says it will begin selling 100,000 robot taxis a year in 2021.



Robotics



1984-87

Carnegie Mellon University and Bundeswehr University Munich develop autonomous vans.



2004

U.S. Defense Department issues a \$1 million challenge to develop self-driving vehicles.

Tesla introduces "autopilot" feature allowing drivers to temporarily take their hands off the wheel.

2014



2016-17

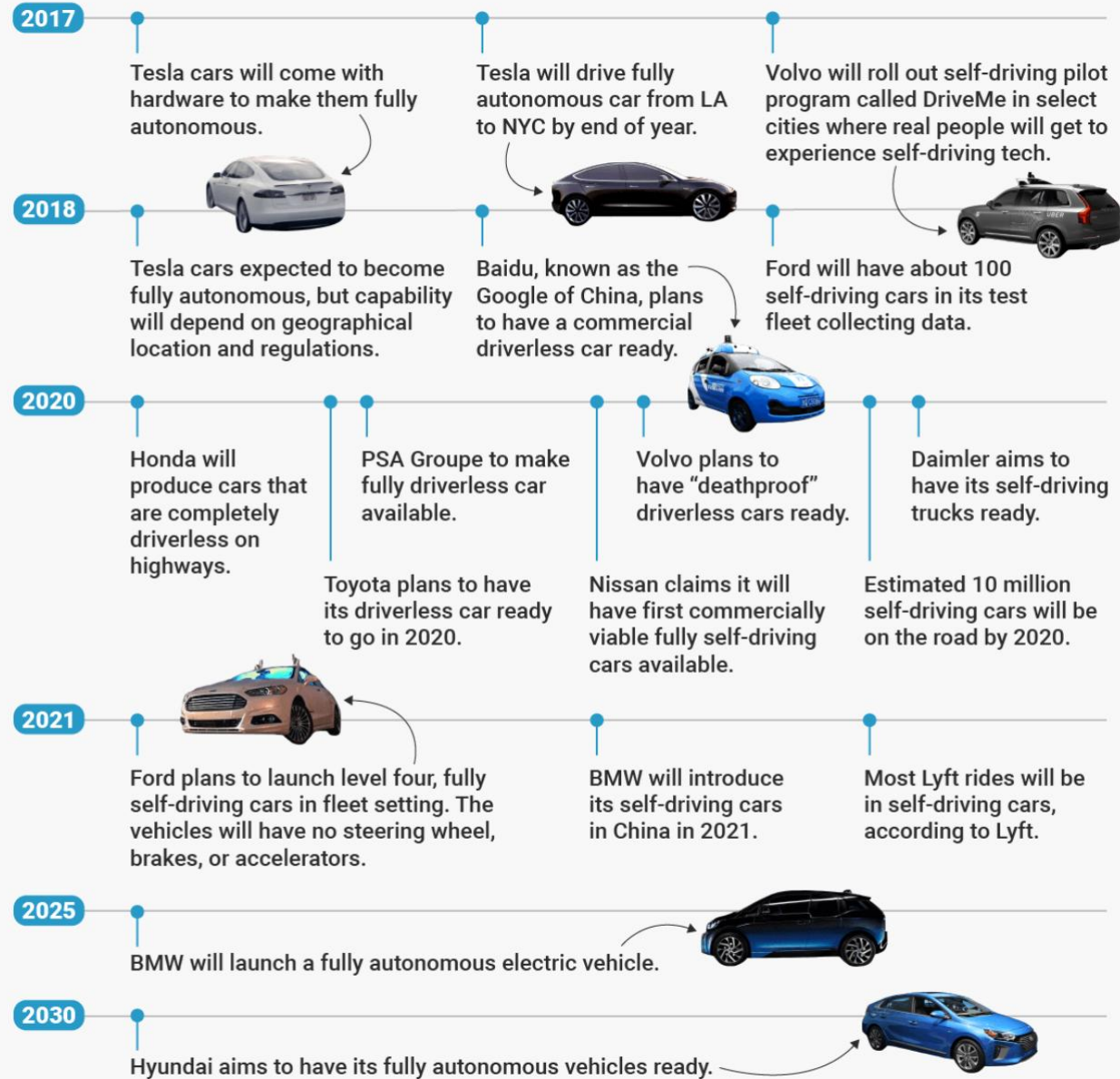
Mercedes, Audi, BMW and Cadillac will offer models that drive hands-free.



History of Autonomous Vehicles (2017 - 2030)

The world's largest Eureka-PROMETHEUS Project is missing ...

Initiative on Autonomous (Water) Surface Vehicles is missing ...



Eureka-PROMETHEUS Project

- The Eureka **PROMETHEUS Project** (*PROgramme for a European Traffic of Highest Efficiency and Unprecedented Safety*, 1987–1995) was the largest R&D project ever in the field of driverless cars. It received €749,000,000 in funding from the EUREKA member states, and defined the state of the art of autonomous vehicles. Numerous universities and car manufacturers participated in this Pan-European project.

Industrial research

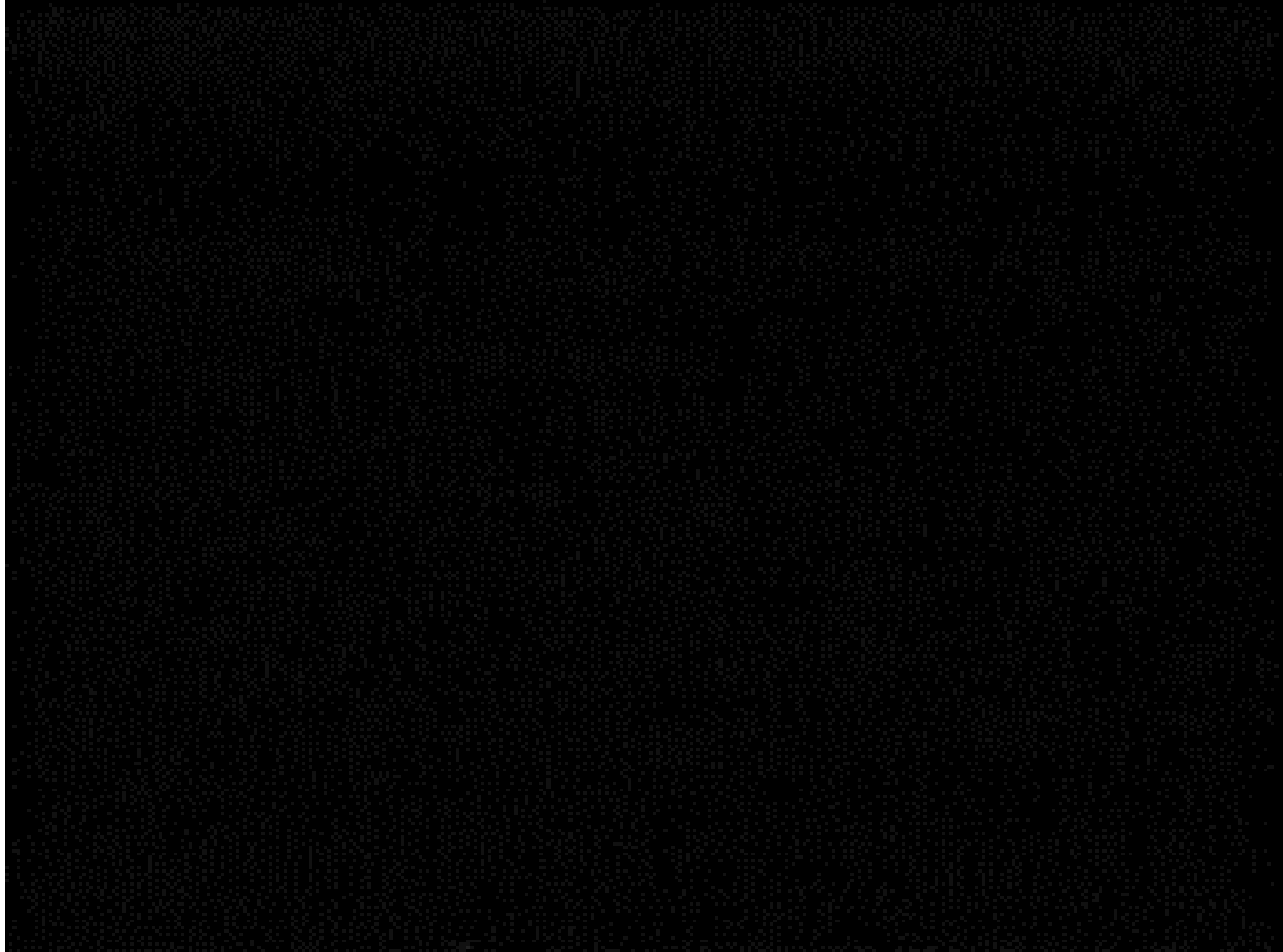
- PRO-CAR : Driver assistance by computer systems
- PRO-NET : Vehicle-to-vehicle communication
- PRO-ROAD : Vehicle-to-environment communication

Basic Research

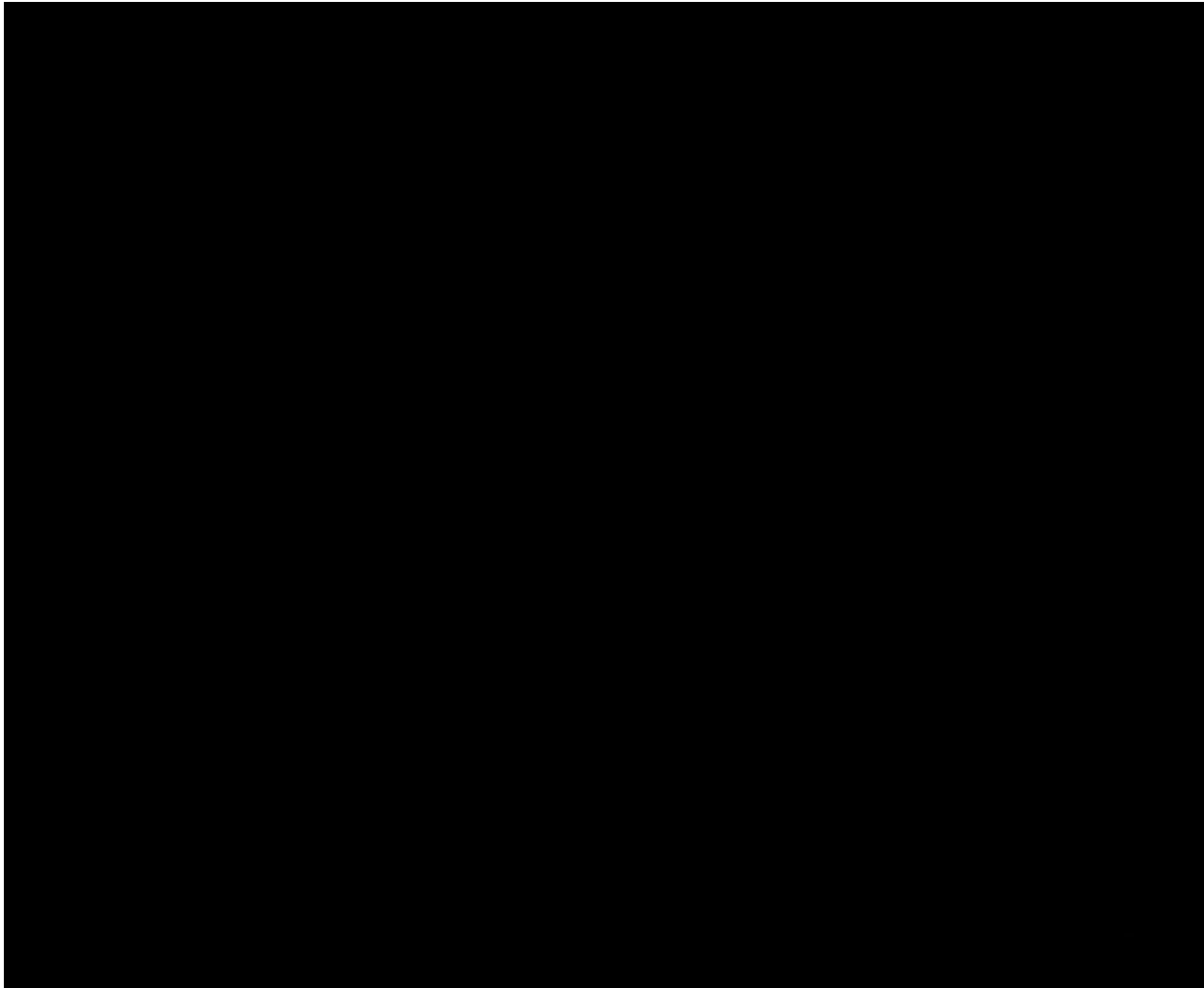
- PRO-ART : Methods and systems of artificial intelligence
- PRO-CHIP: Custom hardware for intelligent processing in vehicles
- PRO-COM : Methods and standards for communication
- PRO-GEN : Traffic scenario for new assessment and introduction of new systems



Video About Eureka-PROMETHEUS



Hybrid Sensing Methodology Developed Around 1991-1993 by Our Team



DARPA Grand Challenge

- The **DARPA Grand Challenge** (2004 - 2007) is a prize competition for American [autonomous vehicles](#), funded by the [Defense Advanced Research Projects Agency](#), the most prominent research organization of the [United States Department of Defense](#). [Congress](#) has authorized DARPA to award cash prizes to further DARPA's mission to sponsor revolutionary, high-payoff research that bridges the gap between fundamental discoveries and military use. The initial DARPA Grand Challenge was created to spur the development of technologies needed to create the first fully [autonomous ground vehicles](#) capable of completing a substantial off-road course within a limited time. The third event, the [DARPA Urban Challenge](#) extended the initial Challenge to autonomous operation in a mock urban environment. The most recent Challenge, the 2012 [DARPA Robotics Challenge](#), focused on autonomous emergency-maintenance robots.

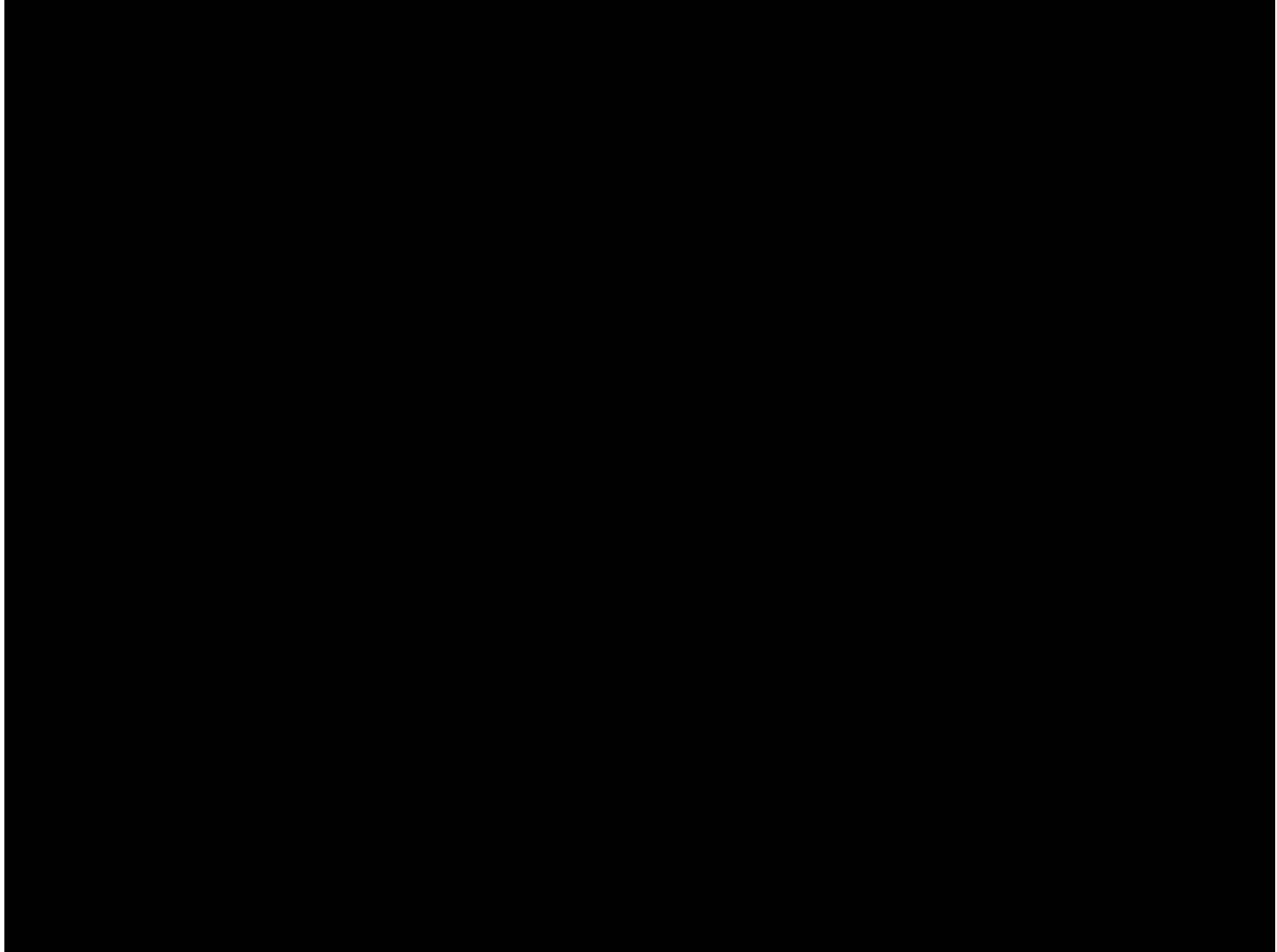


Team Ensco's vehicle that was developed for the 2007 DARPA Urban Challenge

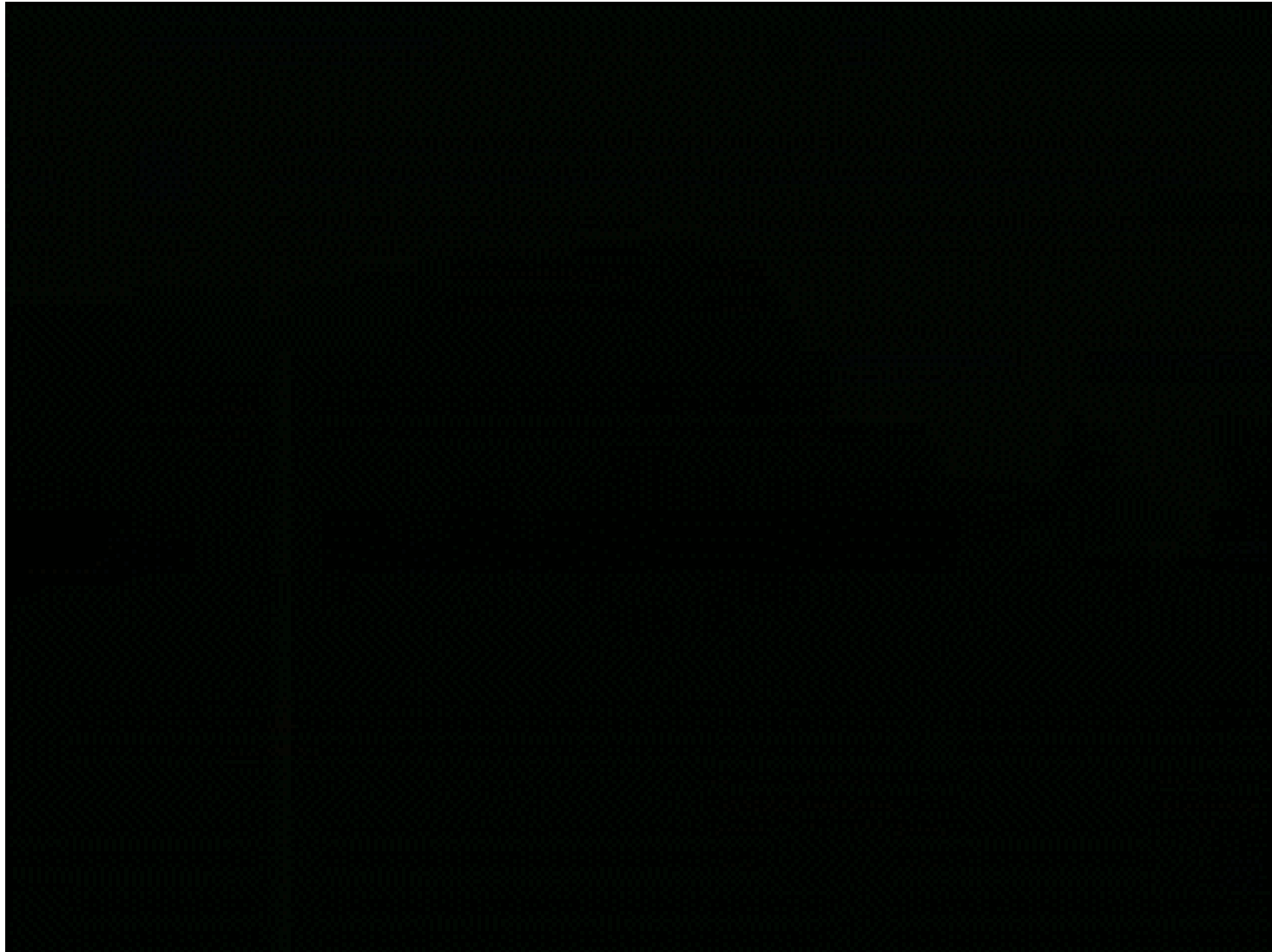


Stanford Racing and Victor Tango together at an intersection in the DARPA Urban Challenge Finals

Video About DARPA Grand Challenge



Our Prototype Developed in 2007



Google's Driverless Cars

- **Waymo (2009 - present)** is an American [autonomous driving](#) technology development company. It is a subsidiary of [Alphabet Inc](#), the parent company of Google. Waymo operates a commercial [self-driving taxi](#) service in the greater [Phoenix, Arizona](#) area called "Waymo One", with [Chandler, Arizona](#) fully mapped. In October 2020, the company expanded the service to the public, and it was the only self-driving commercial service that operates without safety backup drivers in the vehicle at that time. Waymo also develops driving technology for use in other vehicles, including delivery vans and [Class 8](#) tractor-trailers for delivery and logistics.



Tesla's Autopilot

- **Tesla Autopilot** (2013 - present) is a suite of advanced driver-assistance system (ADAS) features offered by Tesla that amounts to Level 2 vehicle automation. Its features are lane centering, traffic-aware cruise control, automatic lane changes, semi-autonomous navigation on limited access freeways, self-parking, and the ability to summon the car from a garage or parking spot. In all of these features, the driver is responsible and the car requires constant supervision. The company claims the features reduce accidents caused by driver negligence and fatigue from long-term driving.



Many Other Initiatives on Land ...

Mercedes-Benz F 015

Volkswagen I.D. Concept

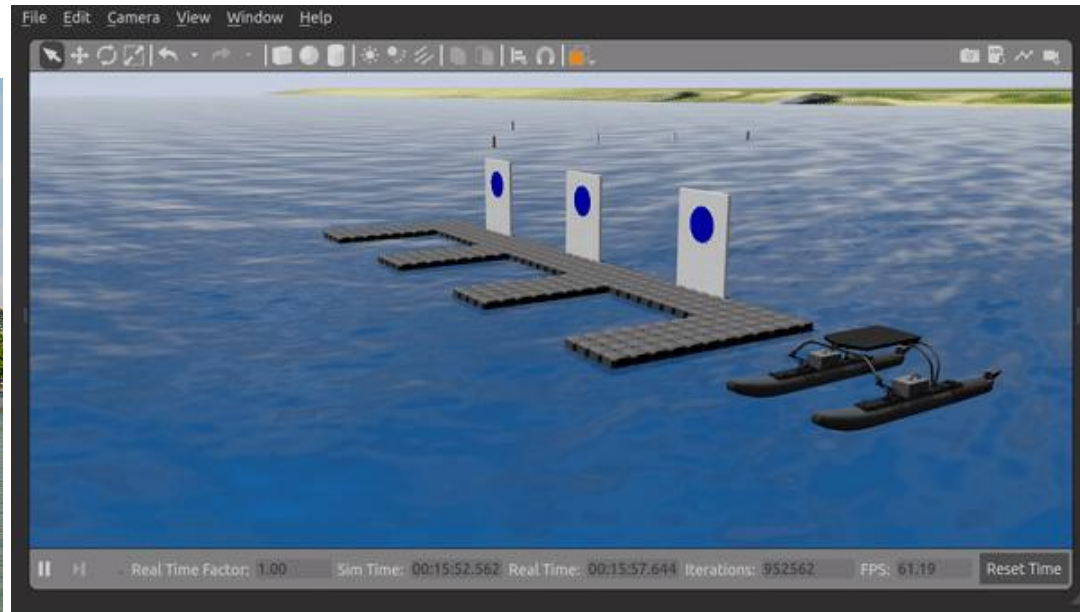


Many Other Initiatives on Land ...



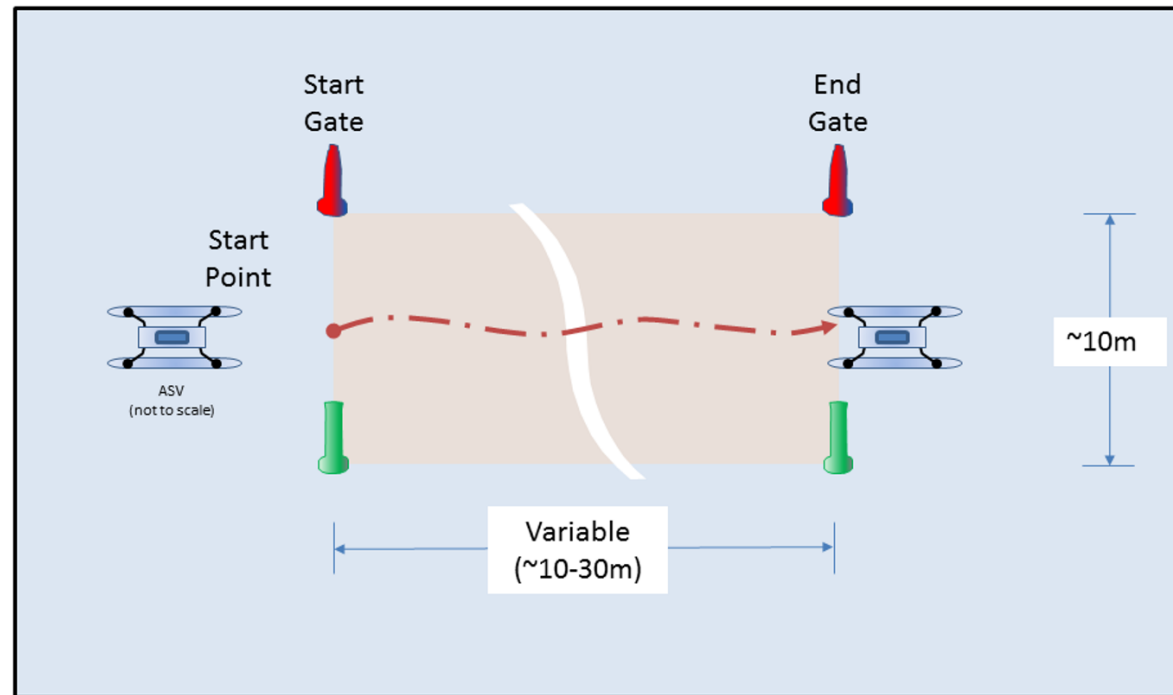
RobotX Maritime Challenge

- RobotX (2014 - present) is a community of innovators driven to create substantive contributions to the field of autonomous, unmanned, multi-domain vehicles. We explore, encourage and make breakthroughs within three key platforms:
 - **Challenge** **Interactive** **Virtual**
- Within these three platforms, participants create new mechanisms, collaborate, form connections and increase proficiency and inventiveness for maritime robotics.



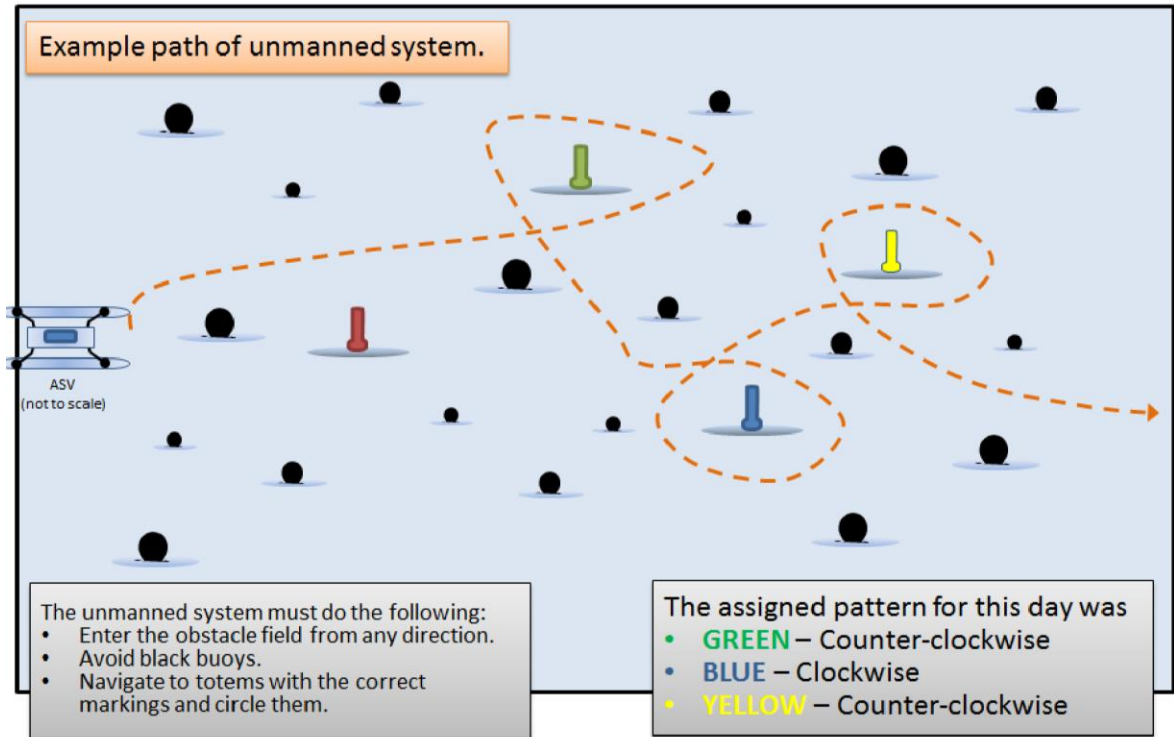
Task 1: Demonstrate Navigation and Control

- The ASV must successfully navigate through two pairs of red and green buoys in a fully autonomous manner, demonstrating effective control of the system. After demonstrating this capability, the ASV will be allowed to proceed to the Team's assigned area.



Task 2: Find Totems and Avoid Obstacles

- The obstacle area may be marked by four white buoys around an area approximately 60m x 60m. The obstacles and totems will be placed inside the area. Entering the obstacle avoidance field and avoiding at least one obstacle or circling any totem will be considered as an attempt at completing this task.



Potential Links to Other Tasks

SCAN THE CODE – The order in which the light pattern flashes will indicate the order in which the vessel must approach and circle the totems.



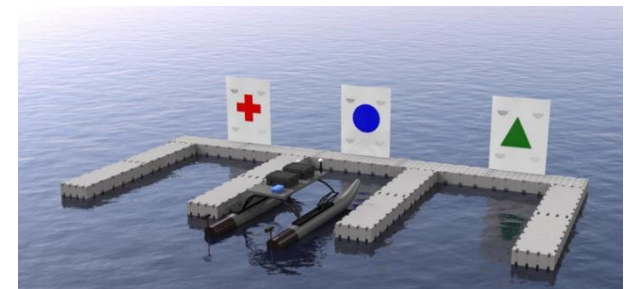
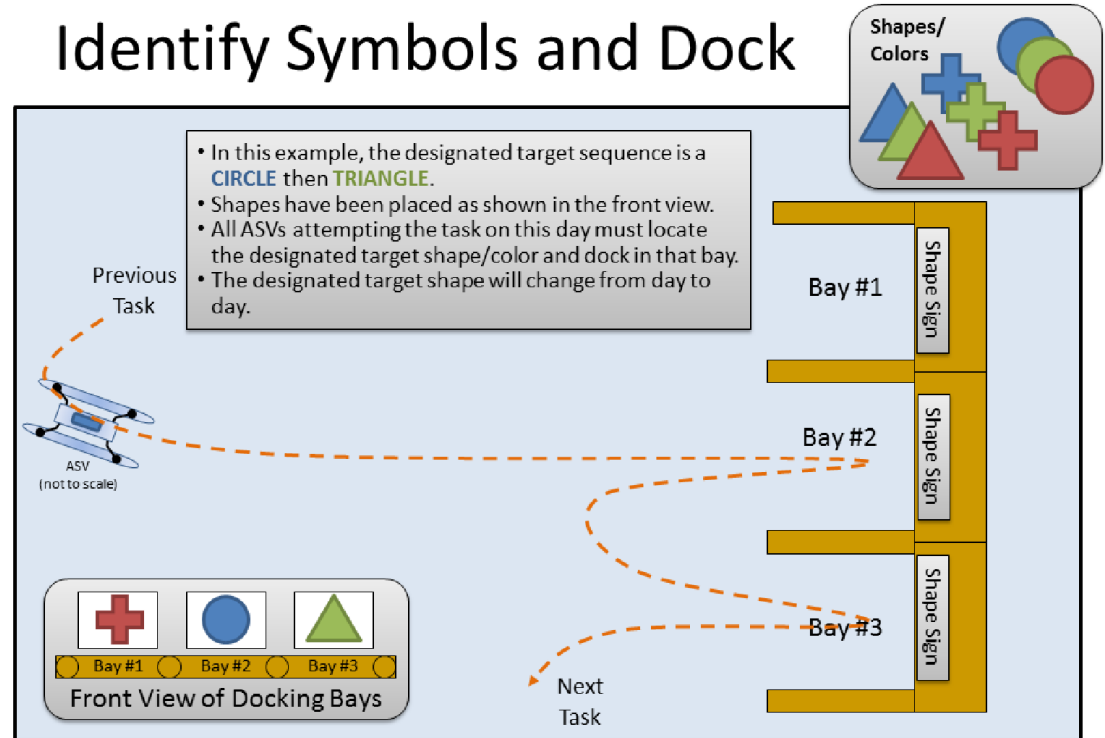
Figure 6. Totem Concept Image

Color	Direction
Red	Clockwise
Green	Counter-clockwise
Blue	Clockwise
Yellow	Counter-clockwise

Task 3: Identify Symbols and Dock

- The ASV must demonstrate the ability to successfully dock in bays identified by a color and shape. The ASV must dock in the bays in the correct sequence. The TD will specify sequences of 2 colored symbols marking each bay. (e.g. "blue cruciform" then "red circle").

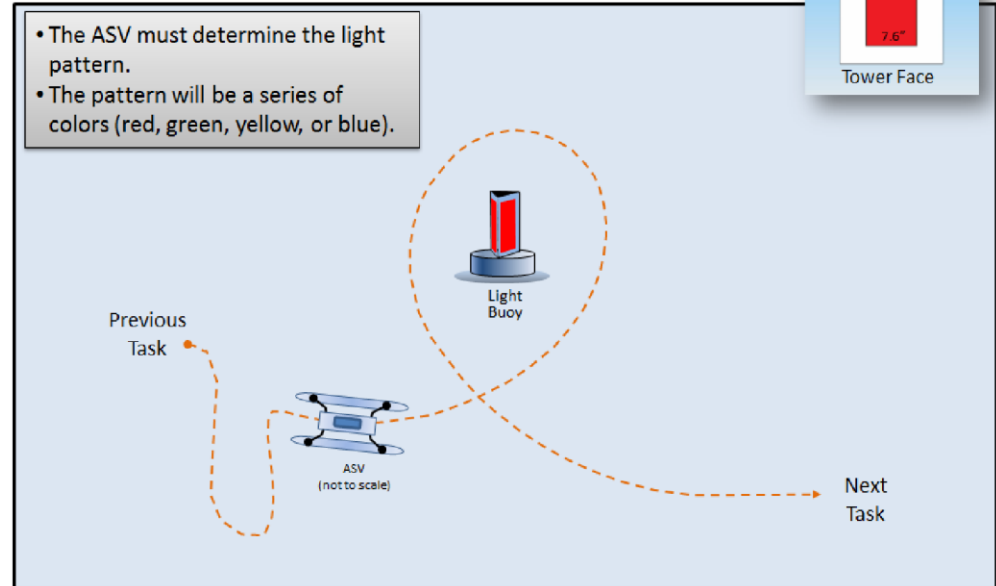
Potential Links to Other Tasks



Task 4: Scan the Code

- The craft will observe a light sequence on an RGB buoy and report the color pattern. This is similar to the 2014 RobotX light buoy task. The added twist will be that we may require the craft to use information from this task to complete another competition task.

Scan the Code



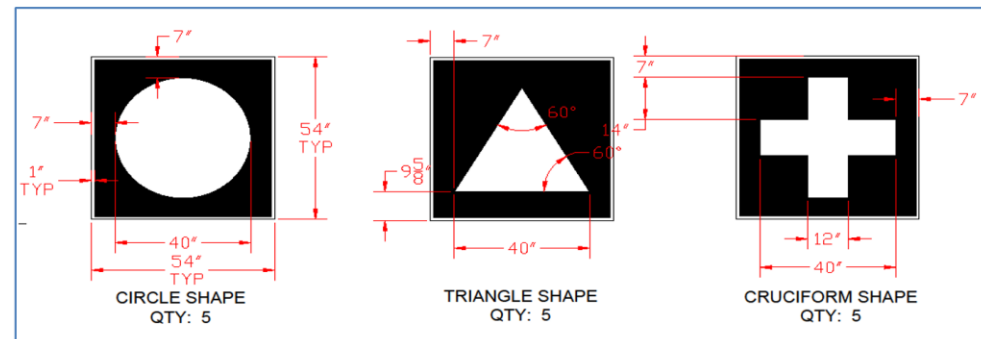
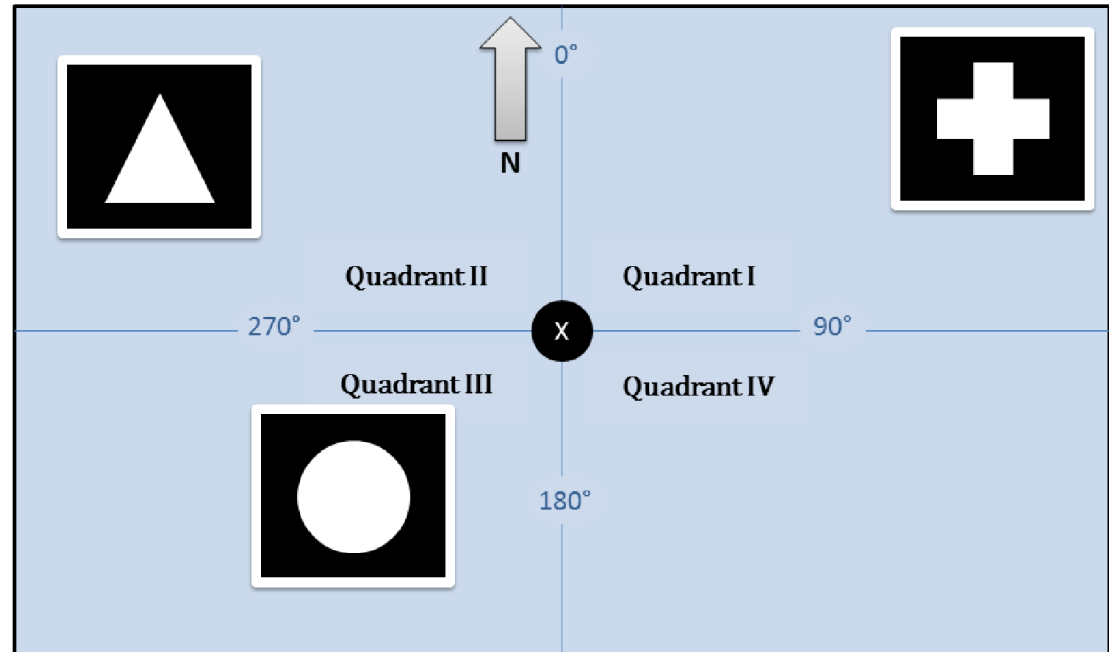
The light assembly on the buoy will successively display colors one at a time to generate a sequential pattern of three colors (e.g., red-green-red). Each individual color will appear for 1 second, after which the lights will remain off (black) for 2 seconds before repeating the same pattern.



Figure 10. Concept Rendering of Scan the Code Task

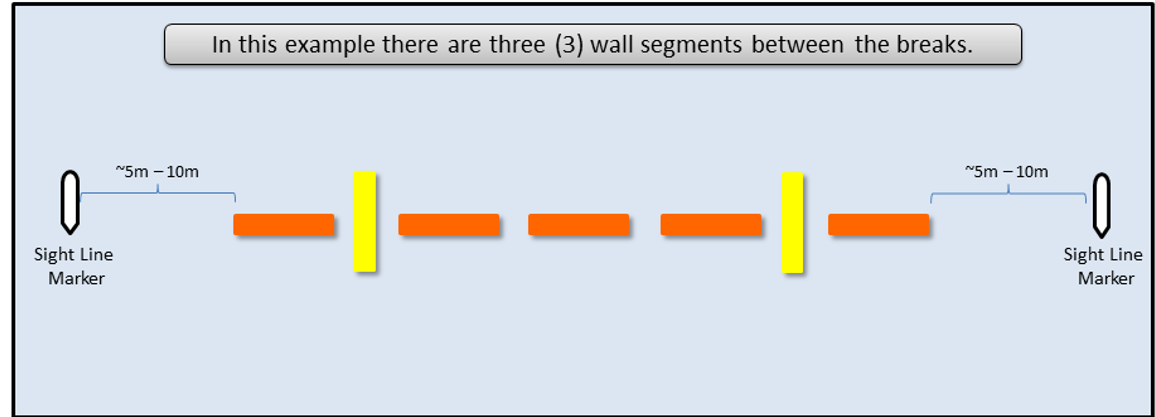
Task 5: Underwater Shape Identification

- The ASV must locate objects on the seafloor given an assigned quadrant relative to a reference buoy. This task requires an underwater sensing capability. The underwater objects will be white shapes on black backgrounds. There will be a white border around the edge of the black background. This task approximates a real-world challenge in which scientists are interested in mapping areas of bleaching coral.

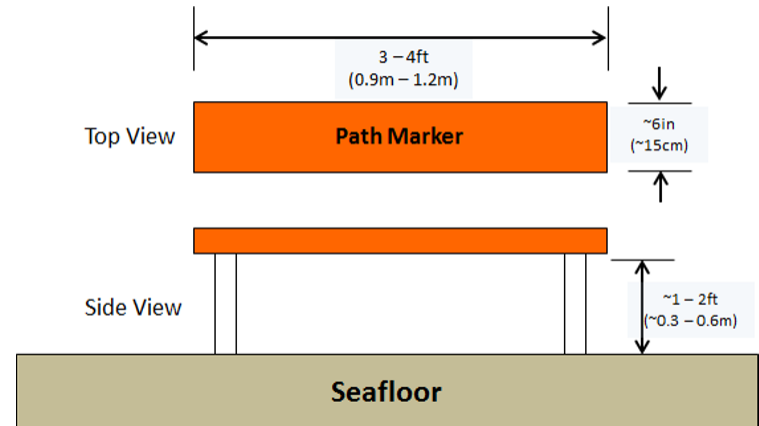


Task 6: Find Underwater Breaks

- Teams must scan markers placed on or near the seafloor (similar to the orange path markers used in RoboSub) and count the segments between a “gap” indicated by other underwater markers.



The number of orange segments between the yellow indicators may be used to indicate which quadrant to search in for the UNDERWATER SHAPE IDENTIFICATION task.



Task 7: Detect and Deliver

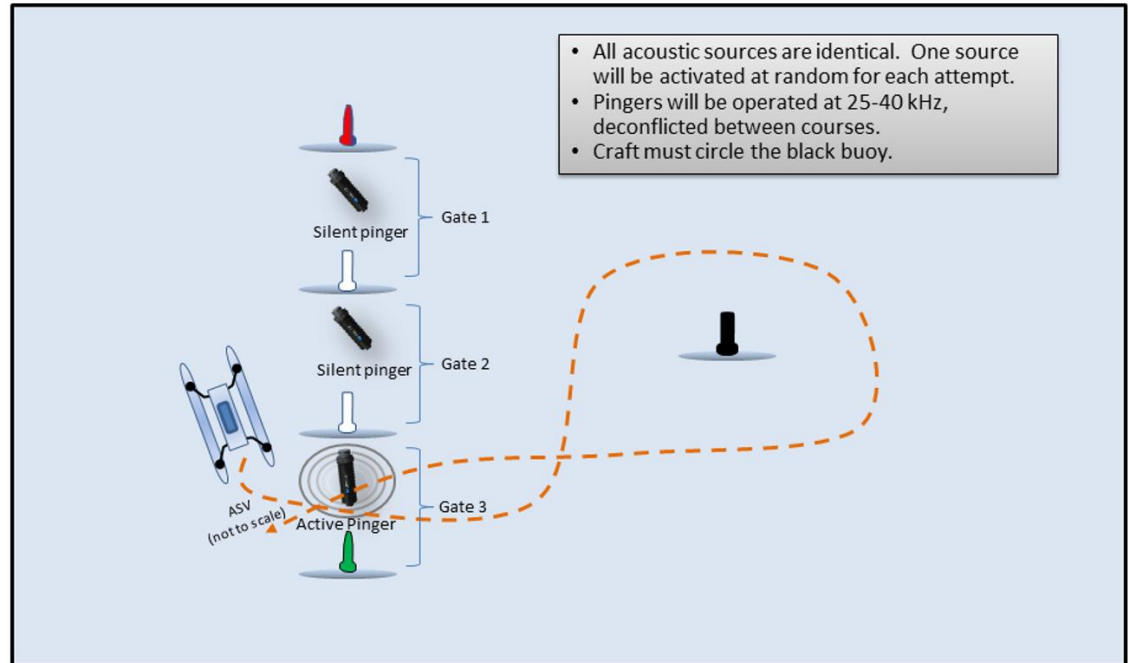
- A four-sided floating platform will be tethered in an open area. Each side of the platform will have a face rising up with a colored shape and a pair of square holes. The ASV must propel or insert objects through the target holes on the face. This task may tie into semi-finals or finals tasks where information from this task is necessary to complete other tasks or information from other tasks is required to complete the Detect and Deliver task.
- For each run, Teams will be provided with four (4) balls.



- The shape from the UNDERWATER SHAPE IDENTIFICATION task may be designated as the target shape for the DETECT AND DELIVER task in the semi-final and final rounds.
- The first color from the SCAN THE CODE task may be designated as the target color for the DETECT AND DELIVER task in the semi-final and final rounds.

Task 8: Acoustic Pinger-Based Transit

- A set of three gates will be located in the practice/qualifying area. There will be a pinger in the middle of each gate. Vehicles must pass through the course and go through the assigned ENTRY and EXIT GATES which will be marked by an underwater acoustic pinger active at the frequencies posted daily. The gate with the active pinger may change between runs.
- A single pinger will be activated at the start of each run to indicate the correct ENTRY GATE and EXIT GATE. The ASV should record the correct gate number for use in combination with other tasks



- The gates will be used to indicate the ENTRY and EXIT points for the Semi-finals or Finals courses. When the ASV crosses through a gate the judges will start or stop the timer measuring time to complete the course.
- This challenge may be combined with the FIND TOTEMS AND AVOID OBSTACLES task so that the active pinger must be located to navigate through the correct ENTRY and EXIT GATES to navigate the obstacle course while locating the correct totems.
- The DETECT AND DELIVER TASK may be placed in between the ENTRY and EXIT GATES so that the ASV must enter the correct ENTRY GATE deliver the balls, then depart through the correct EXIT GATE.
- The ENTRY GATE number (as shown in Figure 16) may represent the quadrant number to search for in the UNDERWATER SHAPE IDENTIFICATION task.

Our Prototype for RobotX 2016

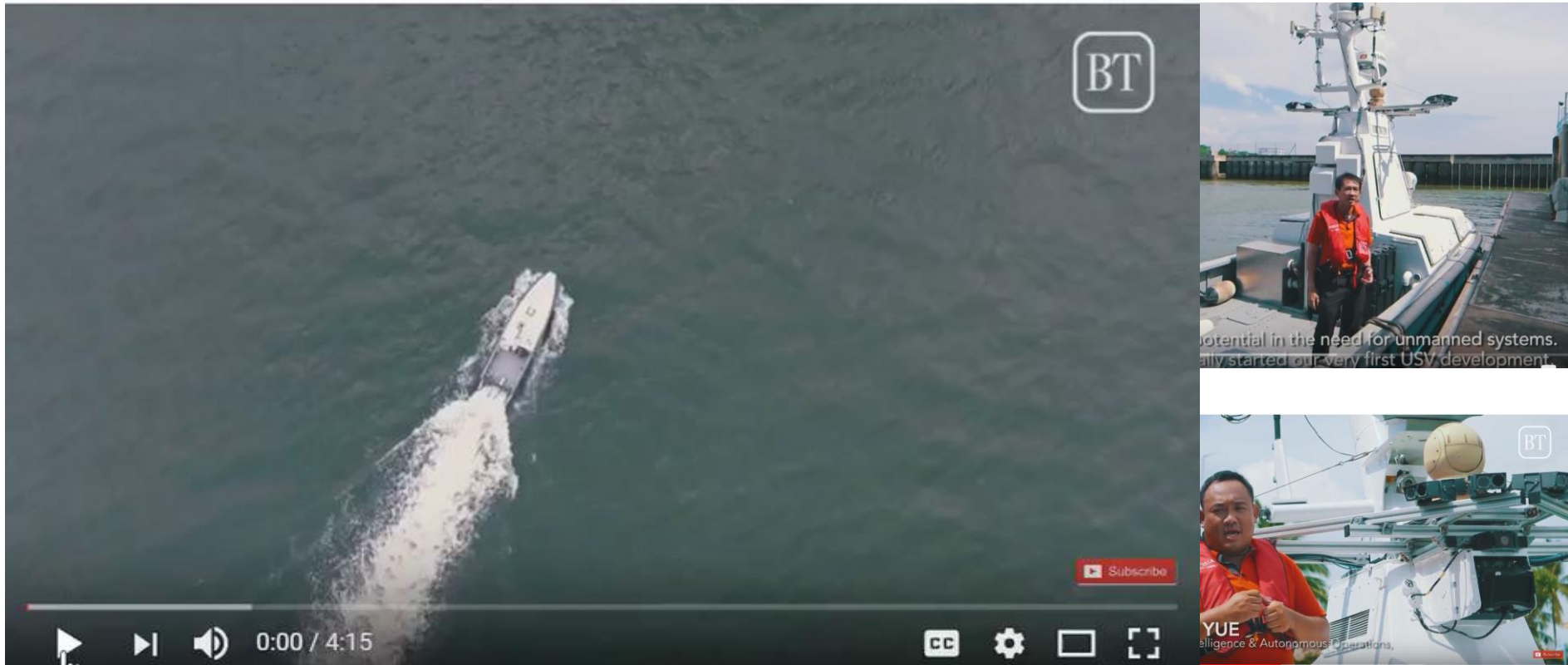
Nanyang Technological University



(Learning, Teaching) <o> (Research, Innovation) <o> (Leadership, Service)

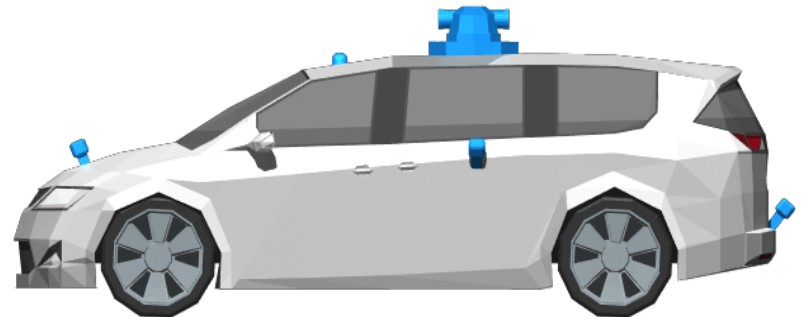


Many Other Initiatives in Sea ...

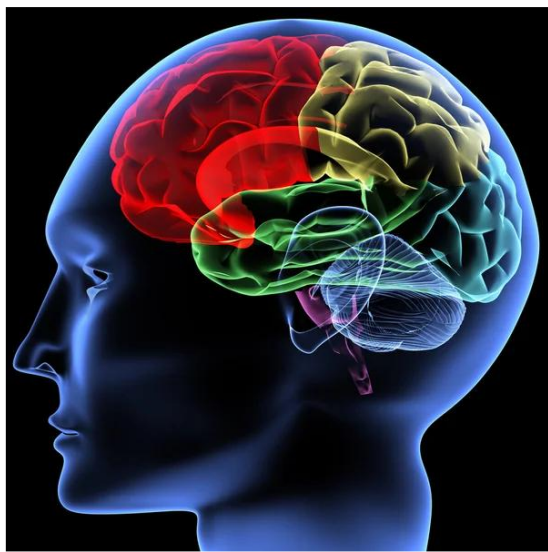
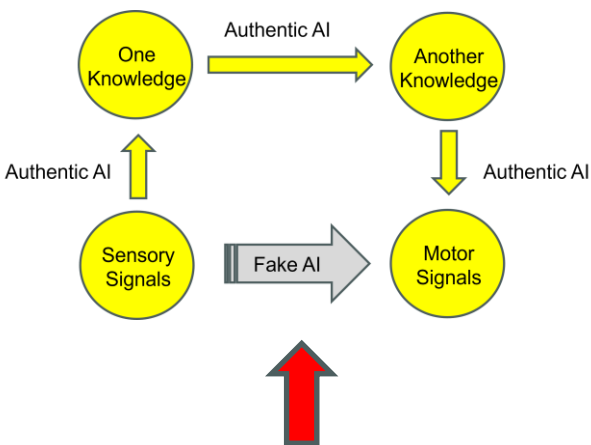


Outline of Today's Talk

- Why to Develop Autonomous Vehicles?
- What is an Autonomous Vehicle?
- What are the Major Initiatives?
- **How to Develop Autonomous Vehicles?**
 - Key Technologies of Perception
 - Key Technologies of Planning
 - Key Technologies of Control
- Future Works



Brain-Centric Philosophy ...



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Adversarial Examples:

- Were discovered in 2013 by **Szegedy et al** and **Biggio et al**
- Have **major security implications and applications**



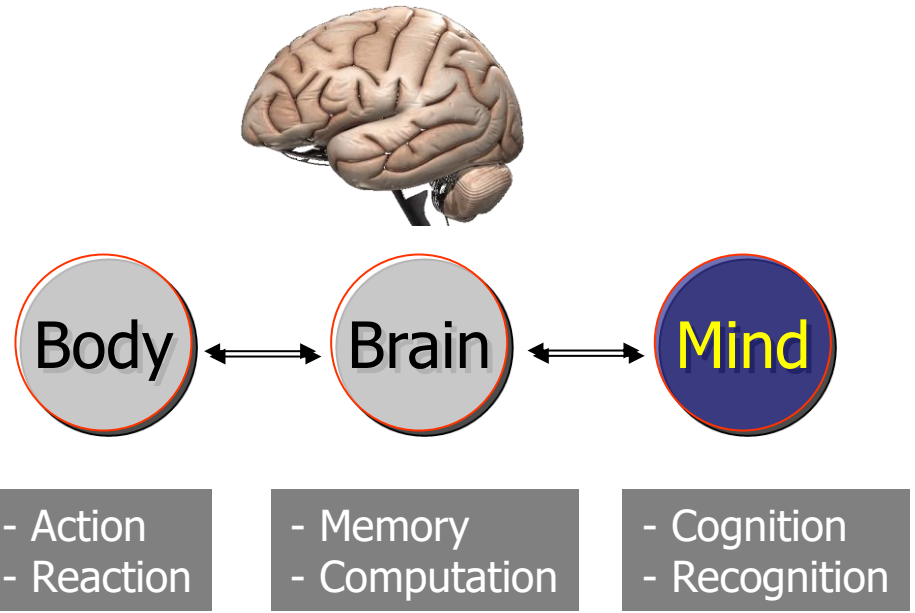

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Pigs can fly:




Mind-Centric Philosophy ...



Last Frontier in Science: “Science of Mind”
How to design machine’s mind?

Coarse Minds
知识

Subtle Minds
意识

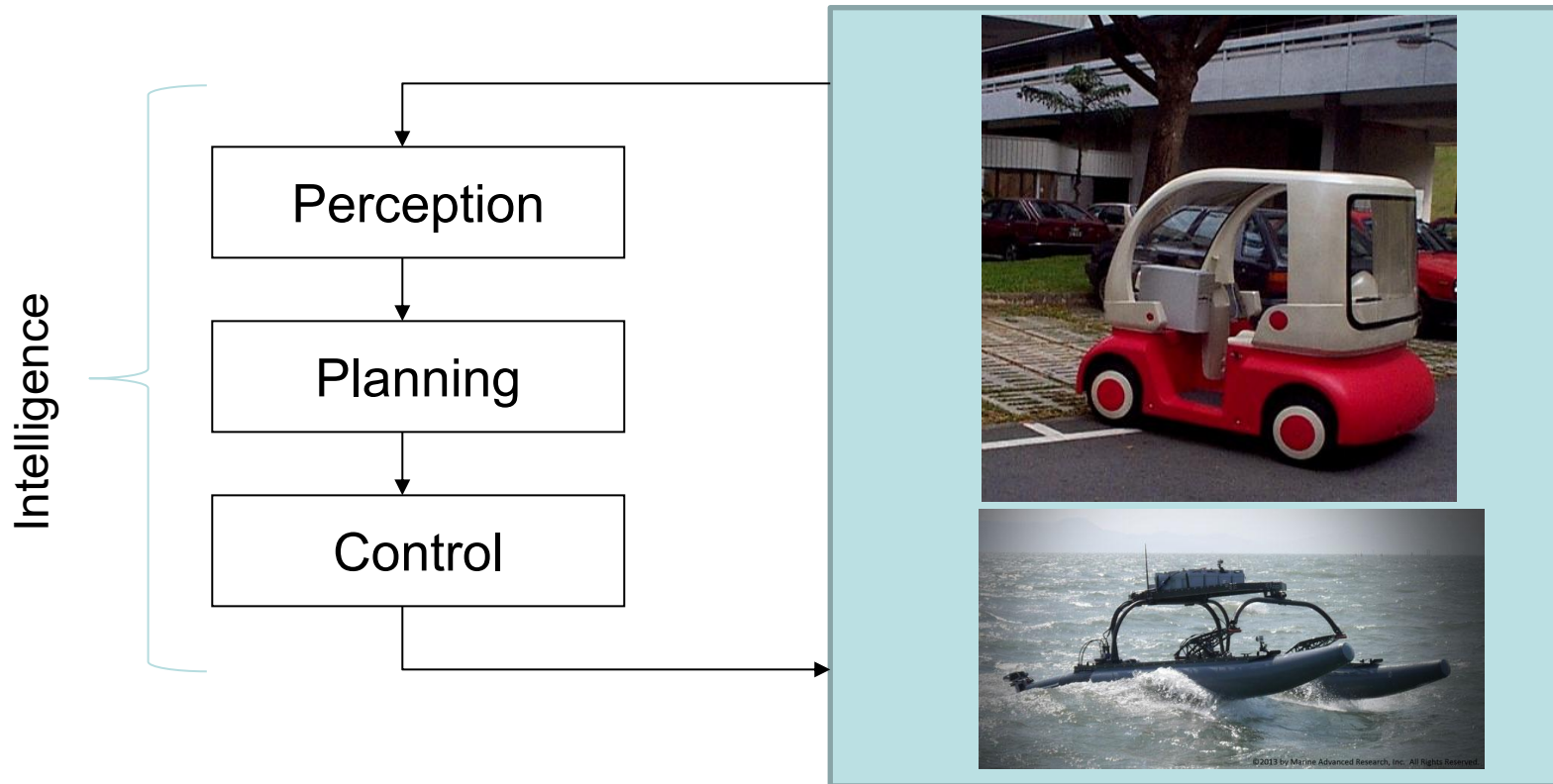


Deep Minds
心识



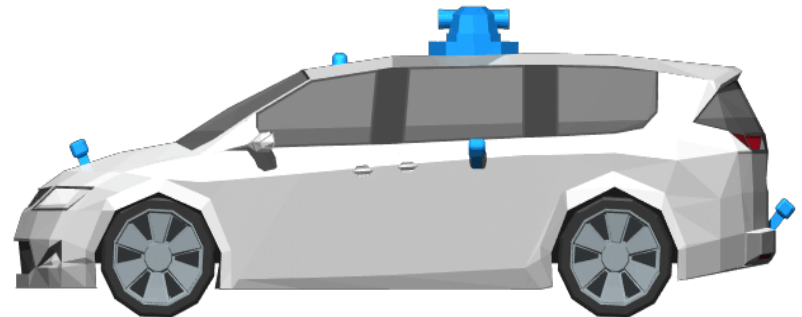
• Soul
• Life

We follow mind-centric approach ...

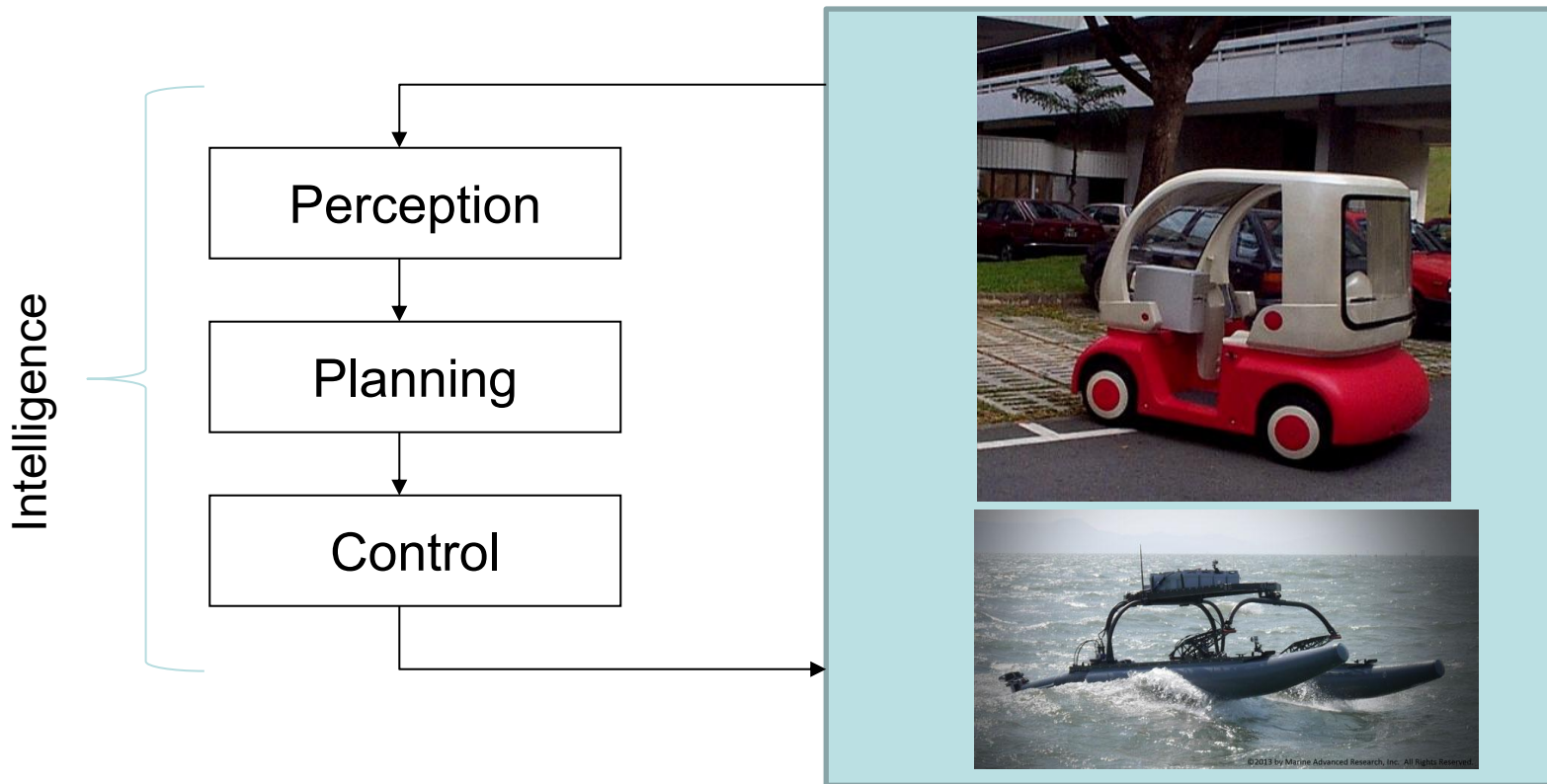


Outline of Today's Talk

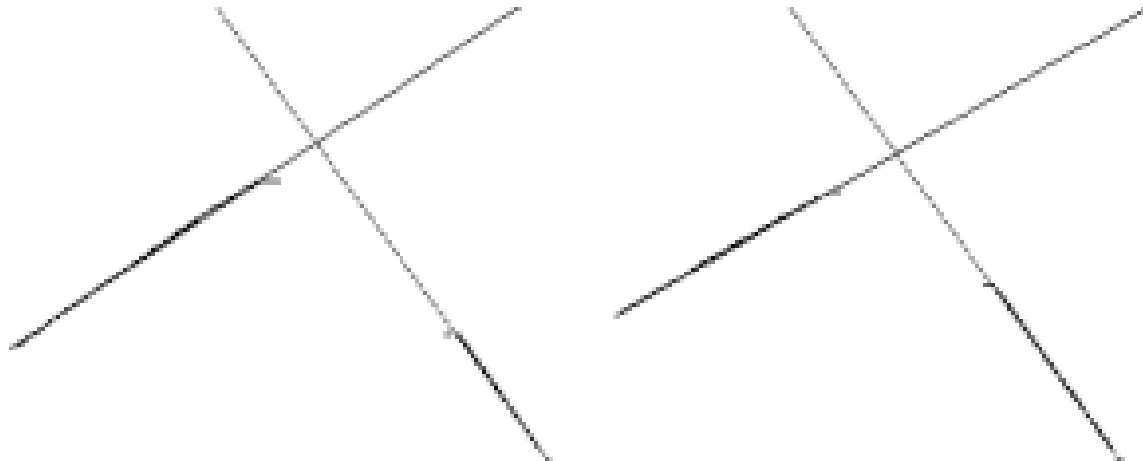
- Why to Develop Autonomous Vehicles?
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The goal of perception is to determine the geometry and the kinematics of scene on a land/water surface



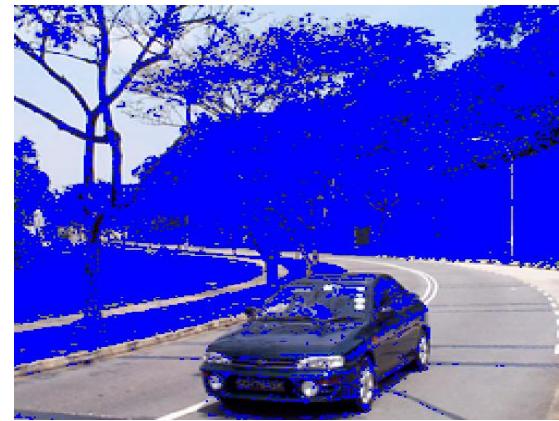
Landmark Detection and Tracking



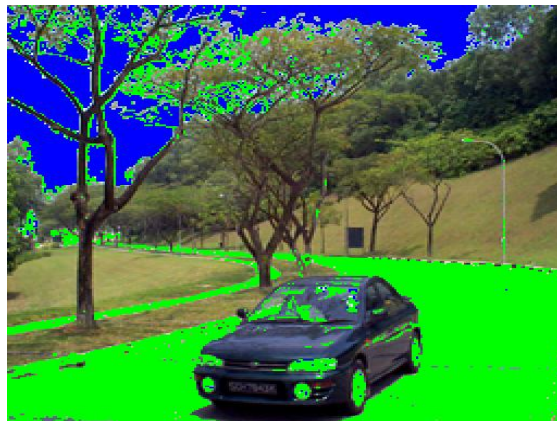
Use of Colour Images to Do Pixel Groupings



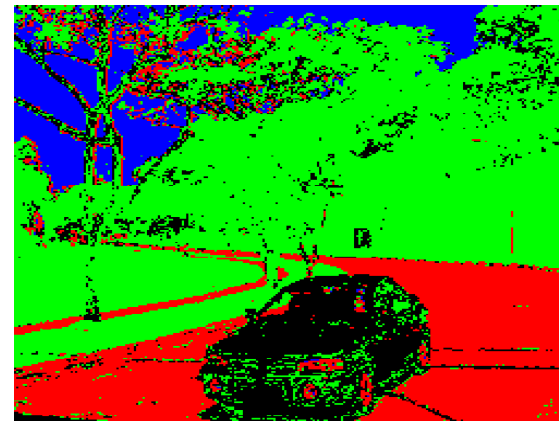
(a). A picture of car



(b). Segmentation of the tree

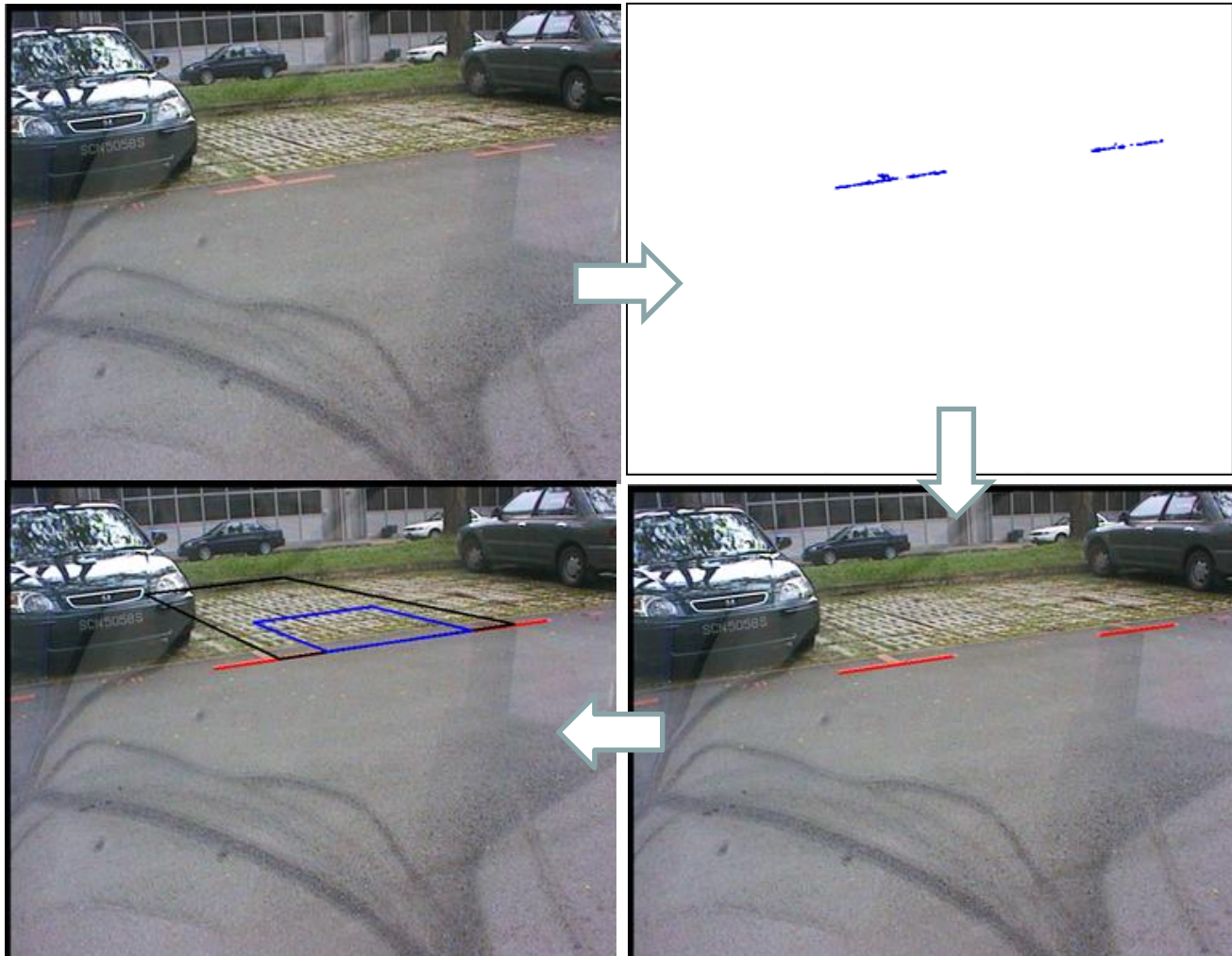


(c). Segmentation of the road and the sky

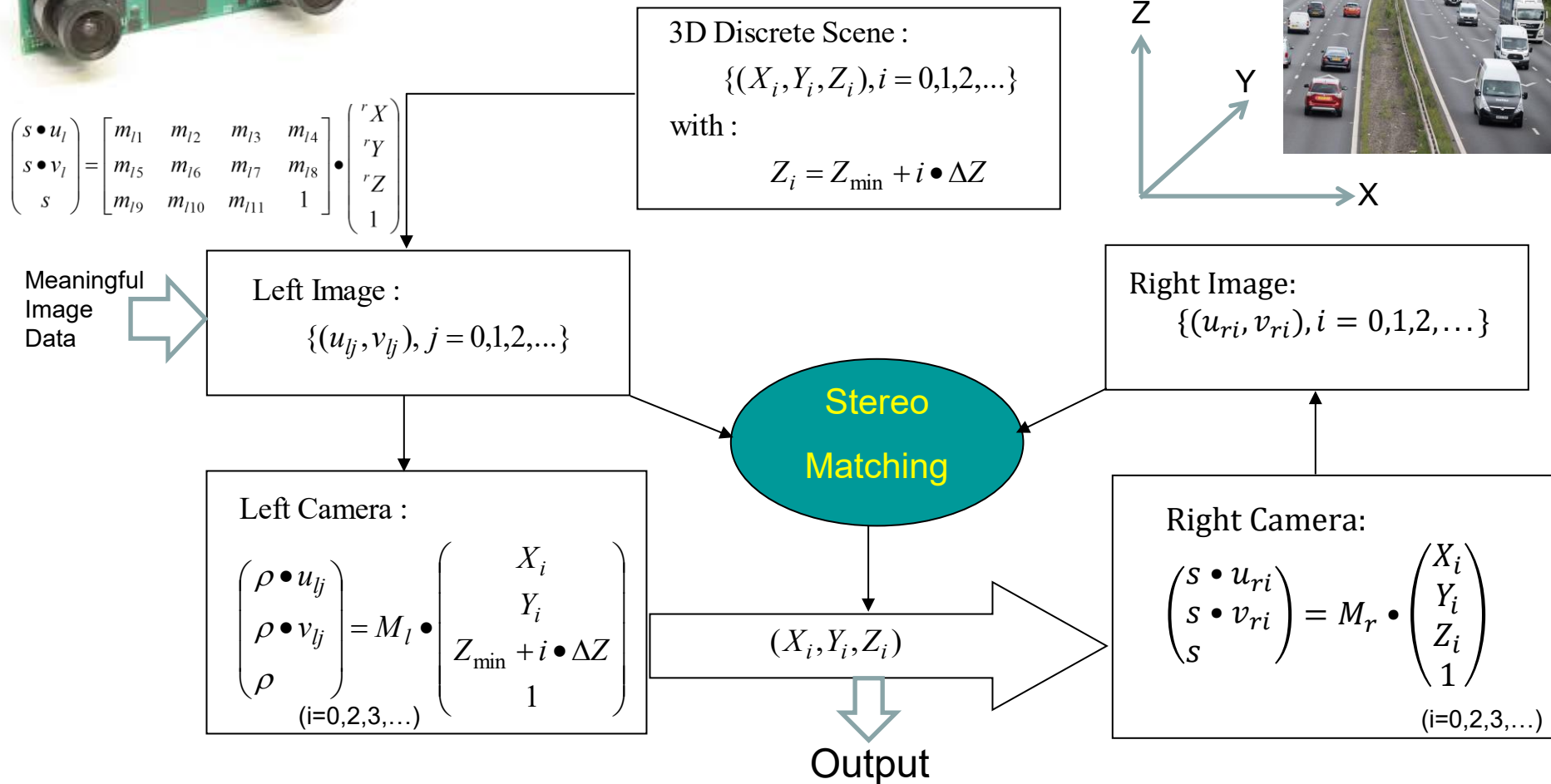


(d). Segmentation of the whole image

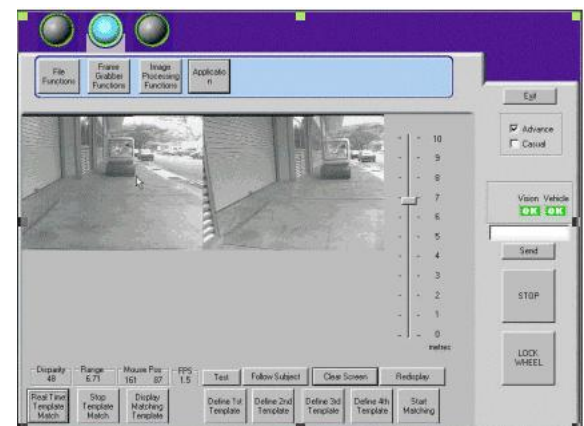
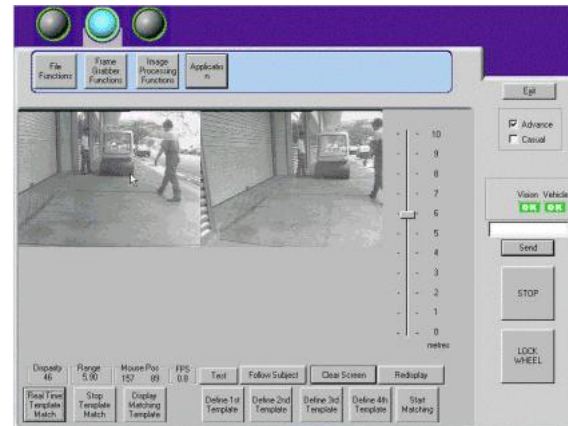
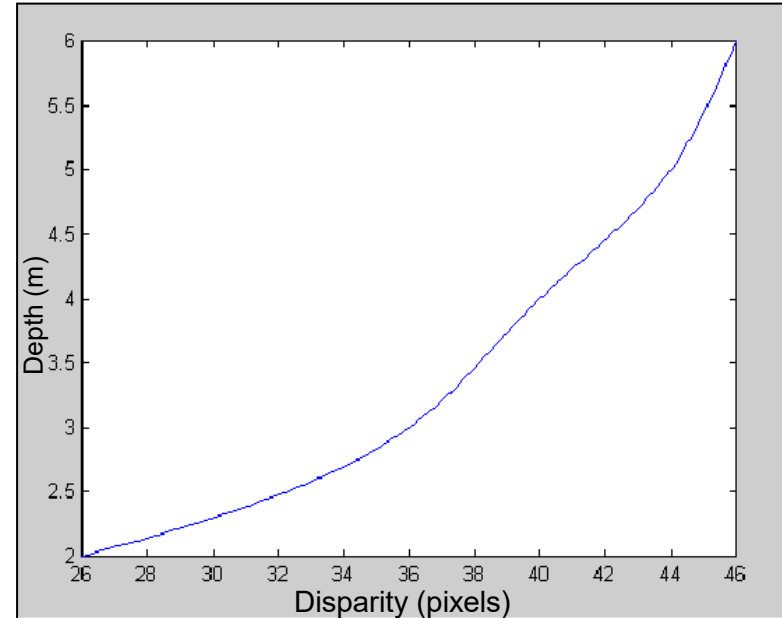
Detection of Empty Parking Lots



Inverse Reconstruction in Binocular Vision



Depth from Qualitative Binocular Vision



Fusion of Multiple Videos Into a Single Video of Sky-view

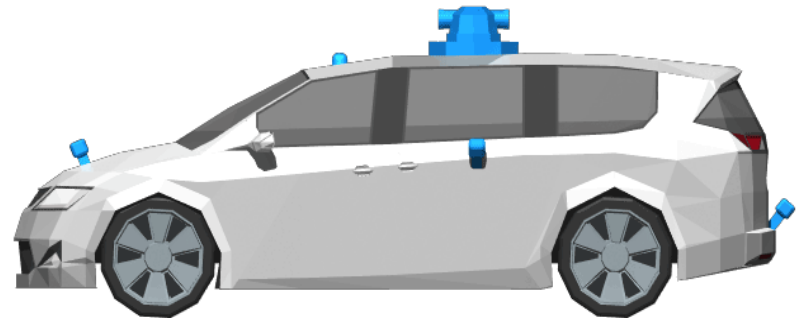


Other Teams' Results ...

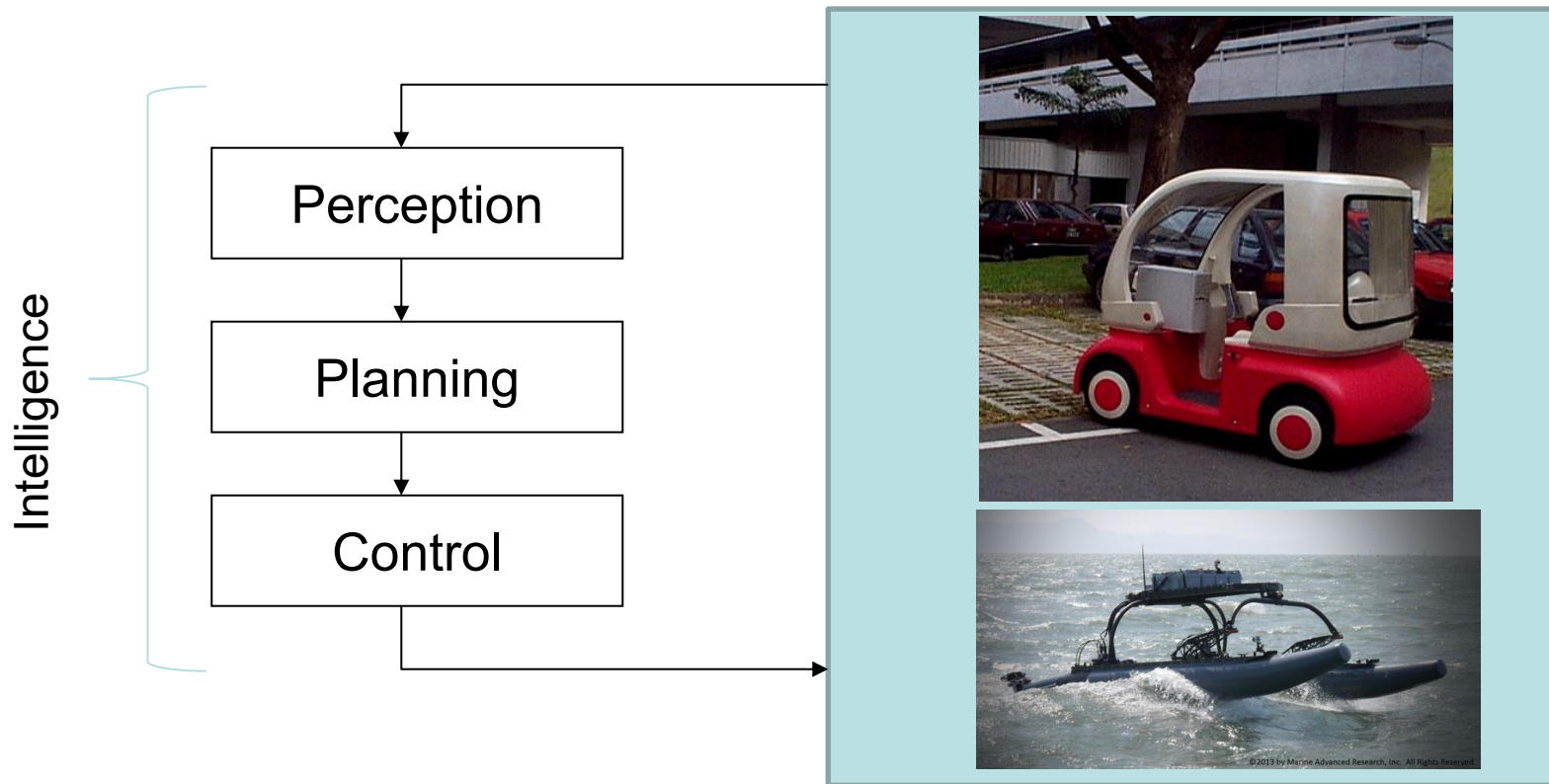


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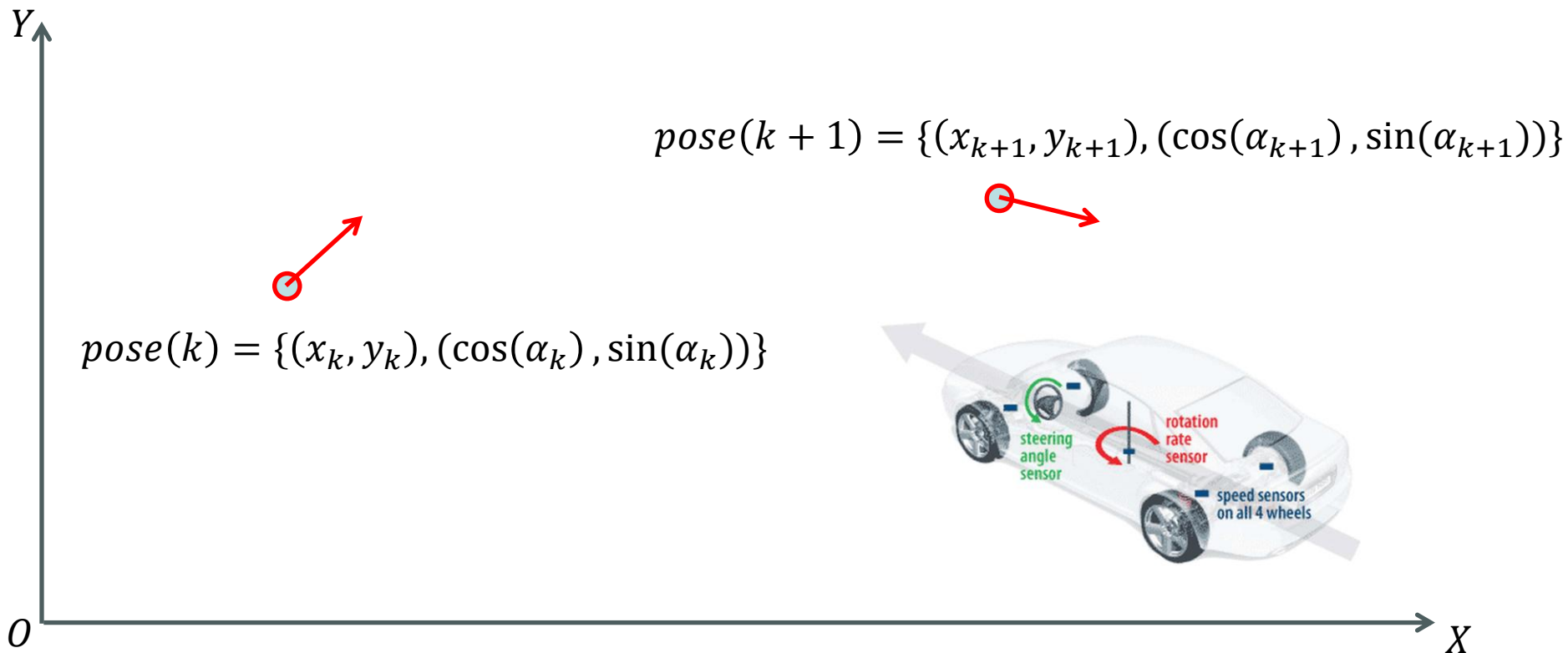


The goal of planning is to determine the equations of desired motions leading to the execution of intended tasks



Problem Description

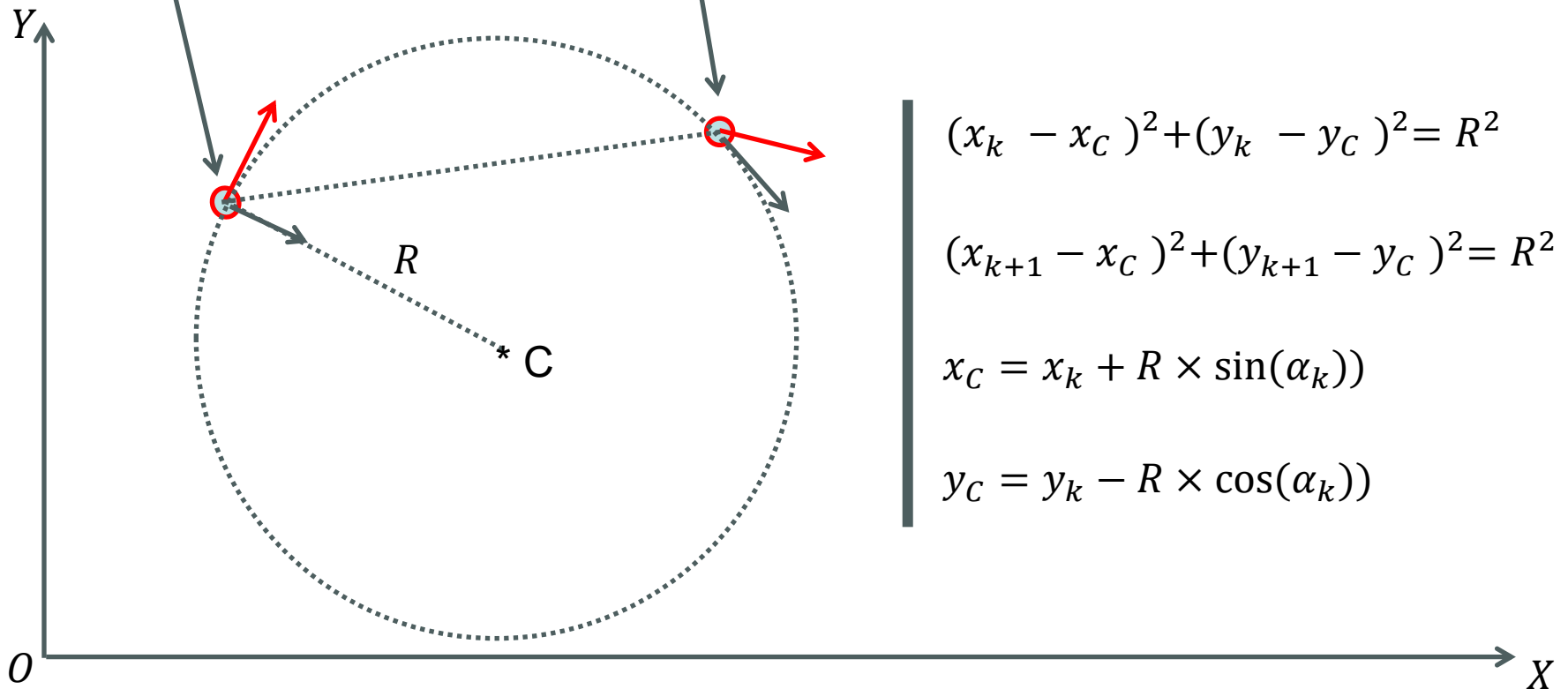
- Given current pose k and next pose $k+1$, how to determine a series of spatial (linear and/or angular) positions which connect pose k to pose $k+1$?



Trivial Solution 1 ...

$$pose(k) = \{(x_k, y_k), (\cos(\alpha_k), \sin(\alpha_k))\}$$

$$pose(k+1) = \{(x_{k+1}, y_{k+1}), (\cos(\alpha_{k+1}), \sin(\alpha_{k+1}))\}$$



$$(x_k - x_C)^2 + (y_k - y_C)^2 = R^2$$

$$(x_{k+1} - x_C)^2 + (y_{k+1} - y_C)^2 = R^2$$

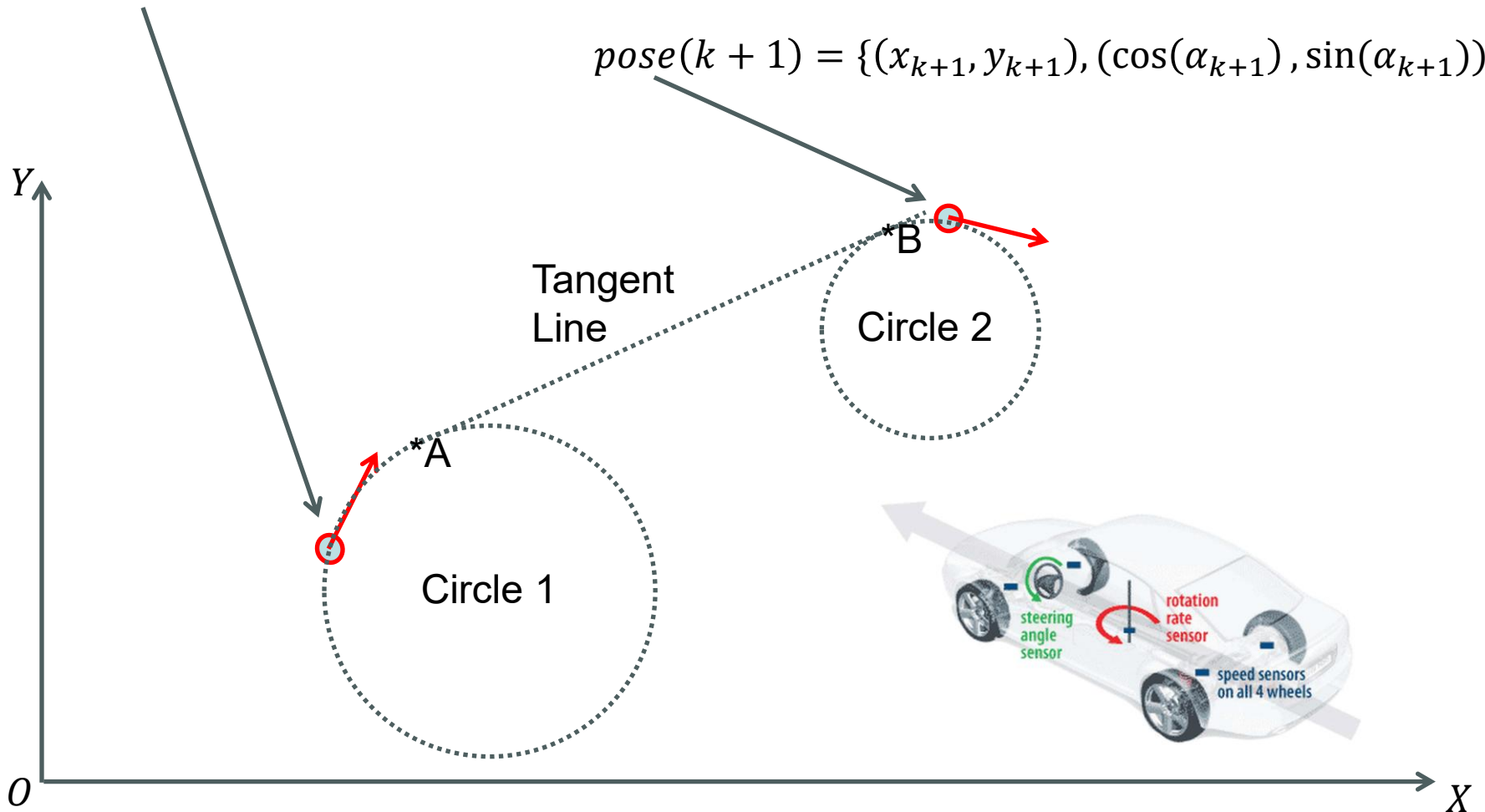
$$x_C = x_k + R \times \sin(\alpha_k)$$

$$y_C = y_k - R \times \cos(\alpha_k)$$

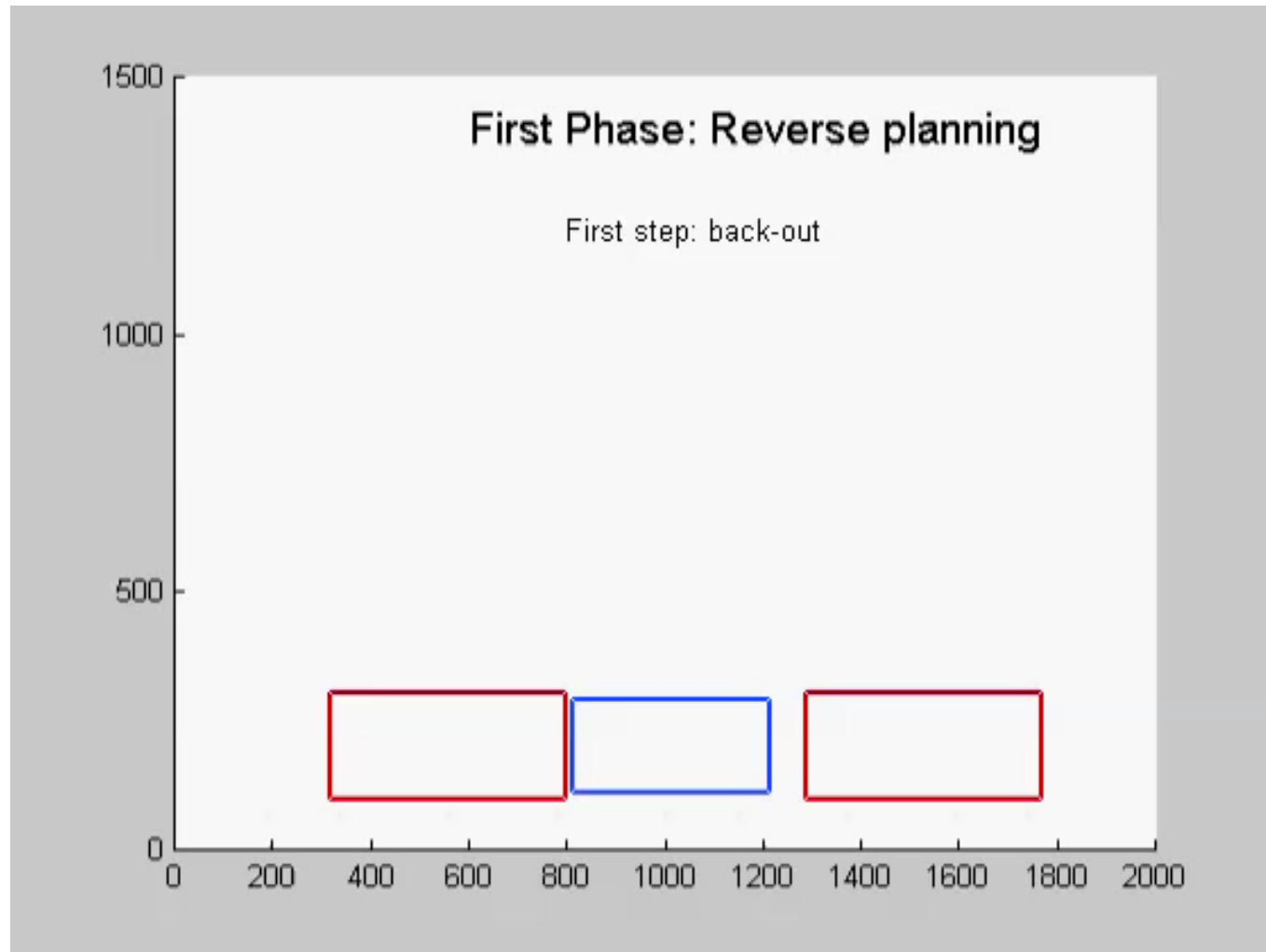
Trivial Solution 2 ...

$$pose(k) = \{(x_k, y_k), (\cos(\alpha_k), \sin(\alpha_k))\}$$

$$pose(k + 1) = \{(x_{k+1}, y_{k+1}), (\cos(\alpha_{k+1}), \sin(\alpha_{k+1}))\}$$



Path Planning with Inverse Motion Planning Strategy Developed in 1999



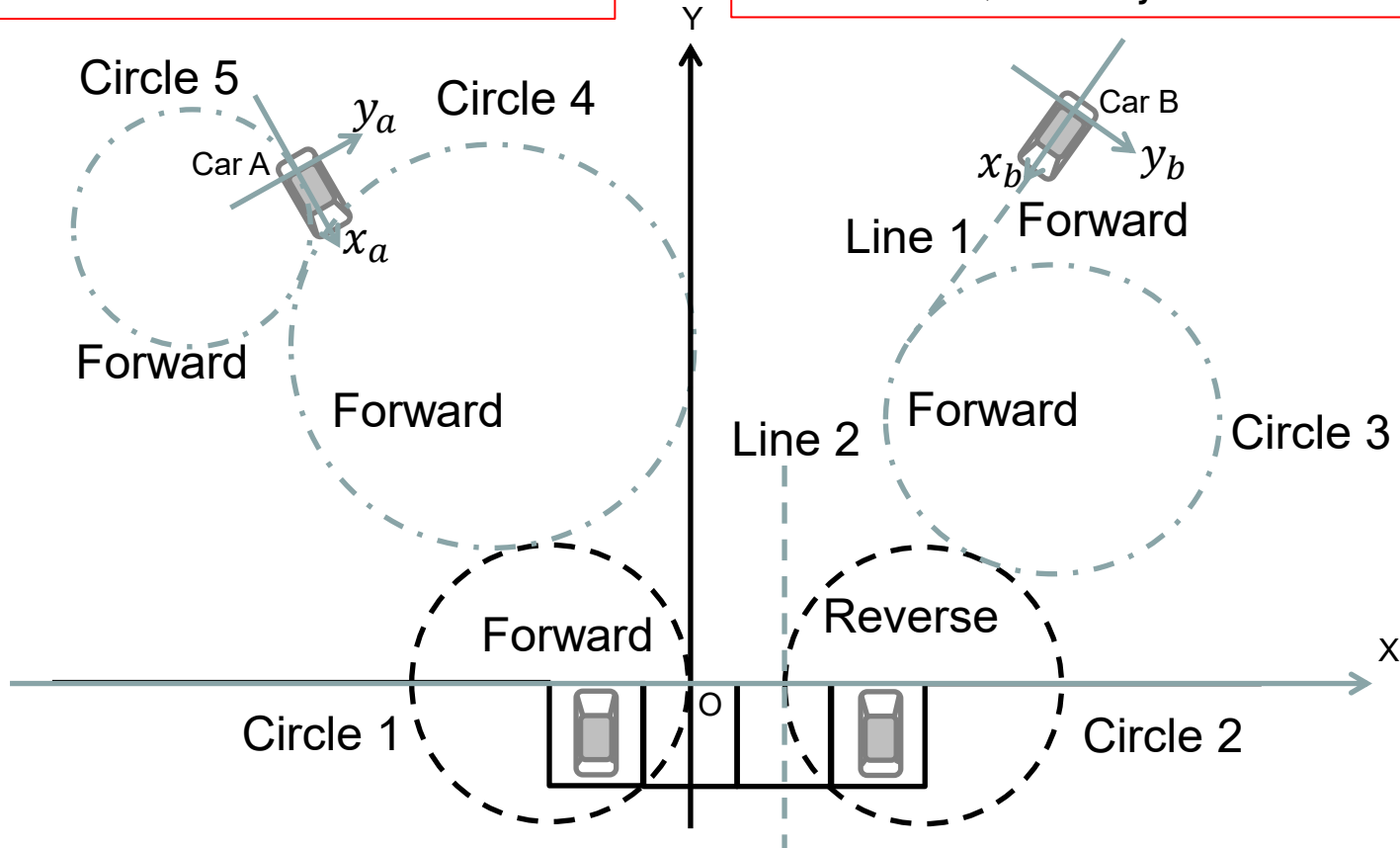
Path Planning with Inverse Motion Planning Strategy

Head-entry to Parking Lot

- Inverse Planning: {Circle 1, Circle 4, Circle 5}
- Forward Motion: {Circle 5, Circle 4, Circle 1}

Tail-entry to Parking Lot

- Inverse Planning: {Line 2, Circle 2, Circle 3, Line 1}
- Forward Motion: {Line 1, Circle 3, Circle 2, Line 2}



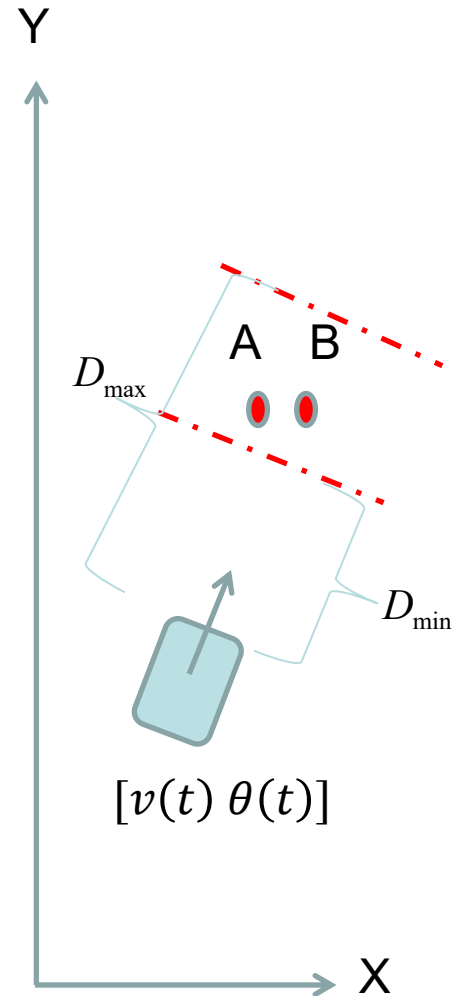
Incremental Planning Solution for Car-like Vehicle

- A car-like vehicle is following a moving target. The vehicle's vision system can measure the distances to points A and B of the moving target. What should be the trajectories of the car-like vehicle?
- Answer:
 - Equation of velocity:

$$v(t_{k+1}) = \begin{cases} v(t_k) + \Delta v & \text{if } d > D_{\max} \\ v(t_k) & \text{if } D_{\min} > d > D_{\max} \\ v(t_k) - \Delta v & \text{if } d < D_{\min} \end{cases}$$

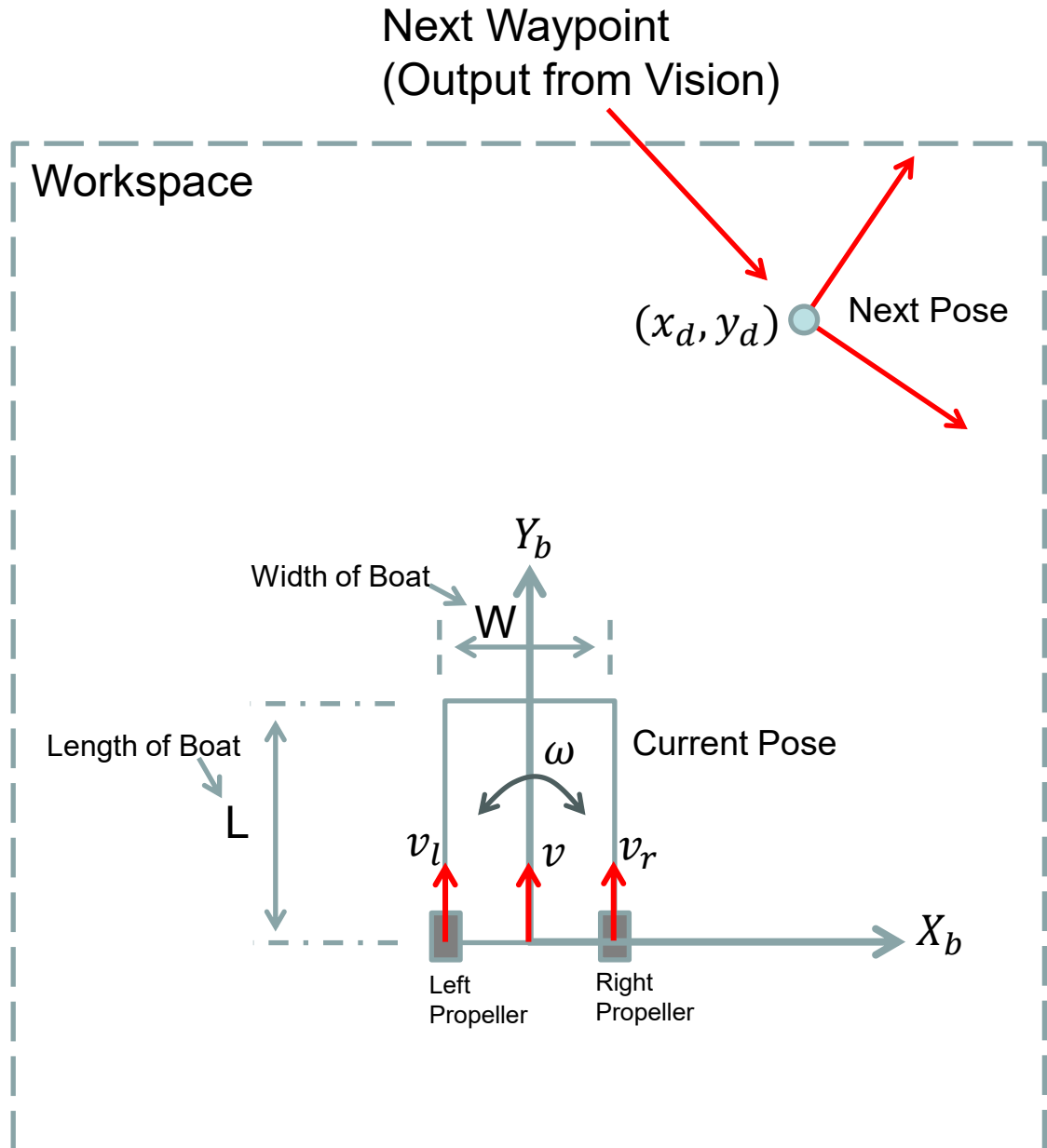
- Equation of steering:

$$\theta(t_{k+1}) = \begin{cases} \theta(t_k) + \Delta \theta & \text{if } d_A - d_B < -\varepsilon \\ \theta(t_k) & \text{if } |d_A - d_B| < \varepsilon \\ \theta(t_k) - \Delta \theta & \text{if } d_A - d_B > +\varepsilon \end{cases}$$



Incremental Planning Solution for Differential Drive Vehicle

- Differential Drive by Wheels
- Differential Drive by Propulsions



Equation of Planning for Differential-Drive Vehicle

Assume that the boat follows a planned circular path with the radius which is equal to R . We have:

1. The angular velocity of the boat:

$$v = \frac{y_d}{y_d + 0.1 \times y_{d,max}} \quad \omega = \frac{v}{R}$$

2. The circular velocity of left propeller:

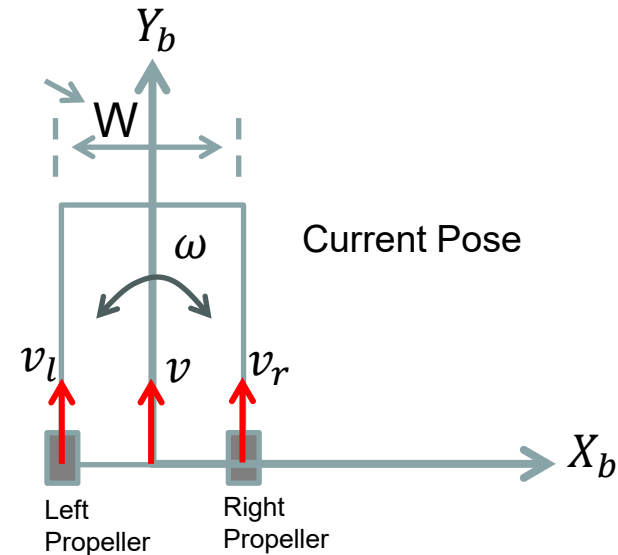
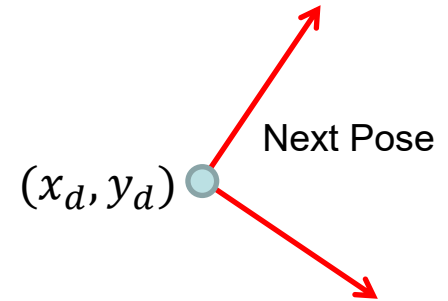
$$v_l = \frac{v}{R} \left(R + \frac{W}{2} \right) = v \left(1 + \frac{W}{2R} \right) = v \left(1 + \frac{W}{2} x_d \right)$$

3. The circular velocity of the right propeller:

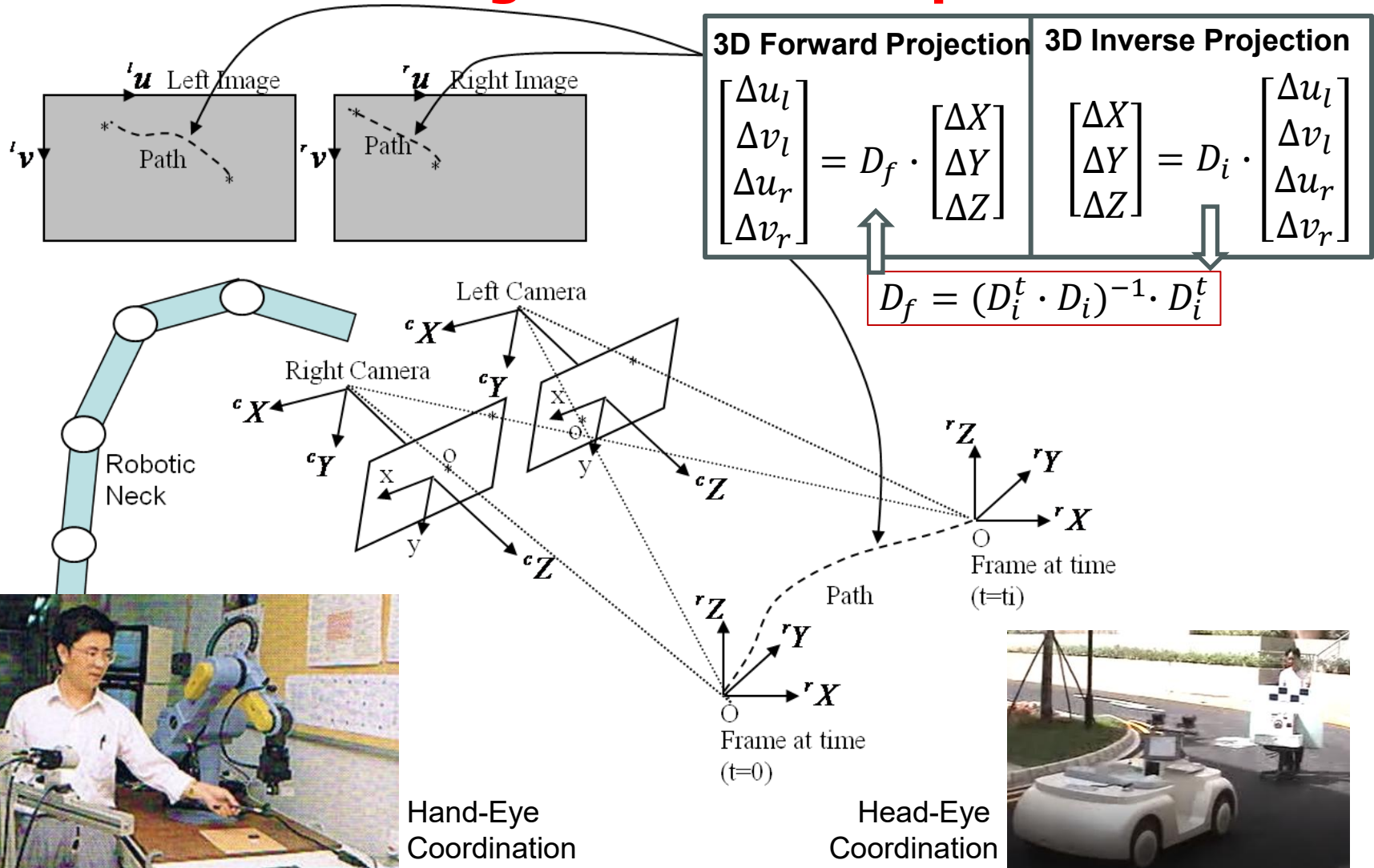
$$v_r = \frac{v}{R} \left(R - \frac{W}{2} \right) = v \left(1 - \frac{W}{2R} \right) = v \left(1 - \frac{W}{2} x_d \right)$$

4. We approximate R with the following value:

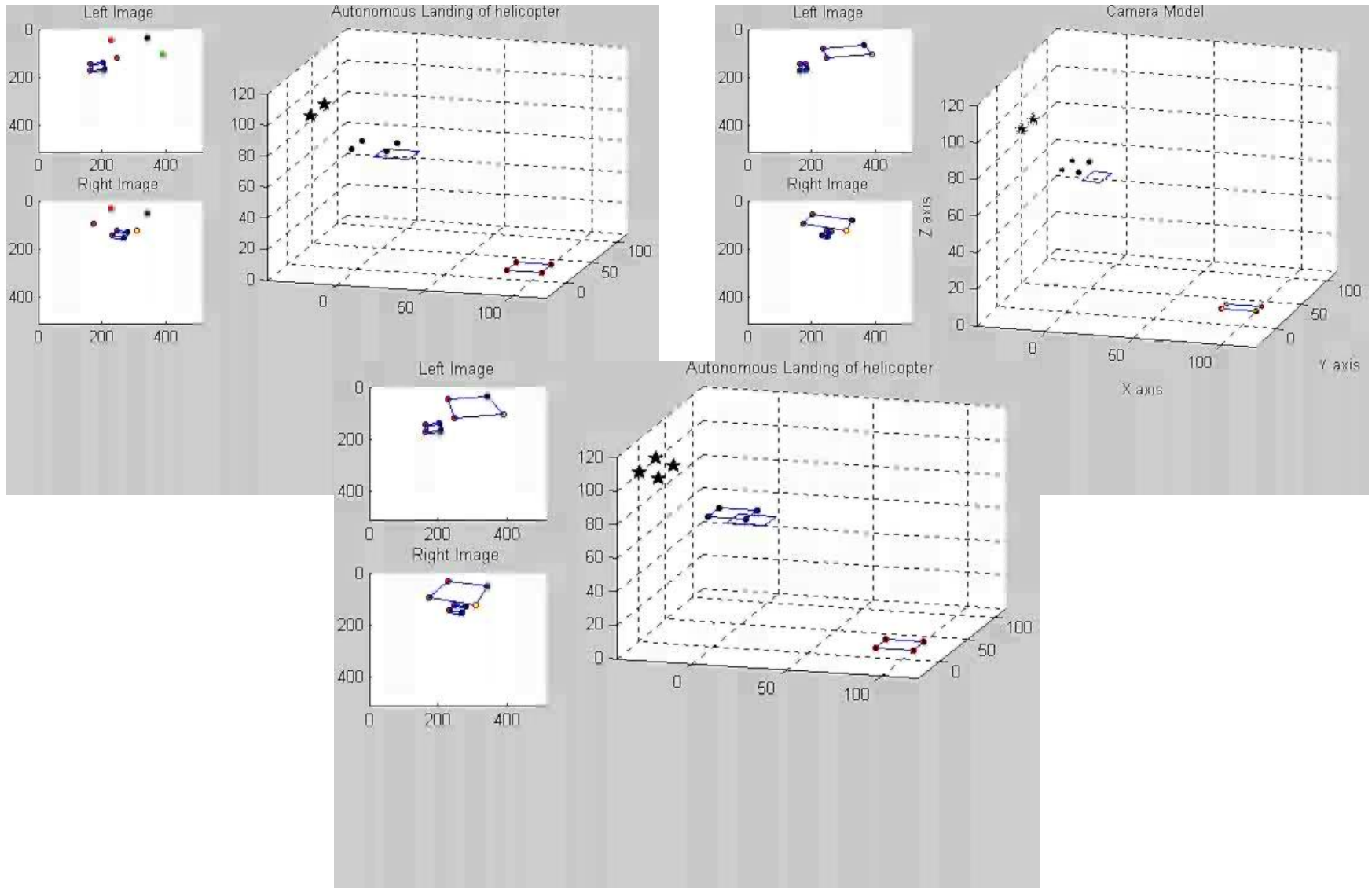
$$R = \frac{1}{x_d}$$



On-fly Motion Planning with X-Eye Coordination Algorithm Developed in 1997

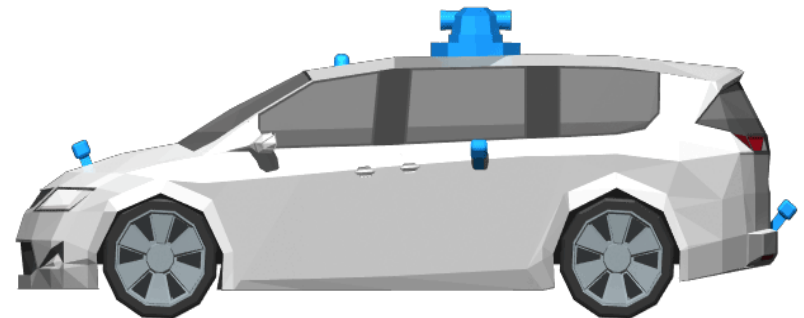


X-Eye Coordination for Automatic Landing

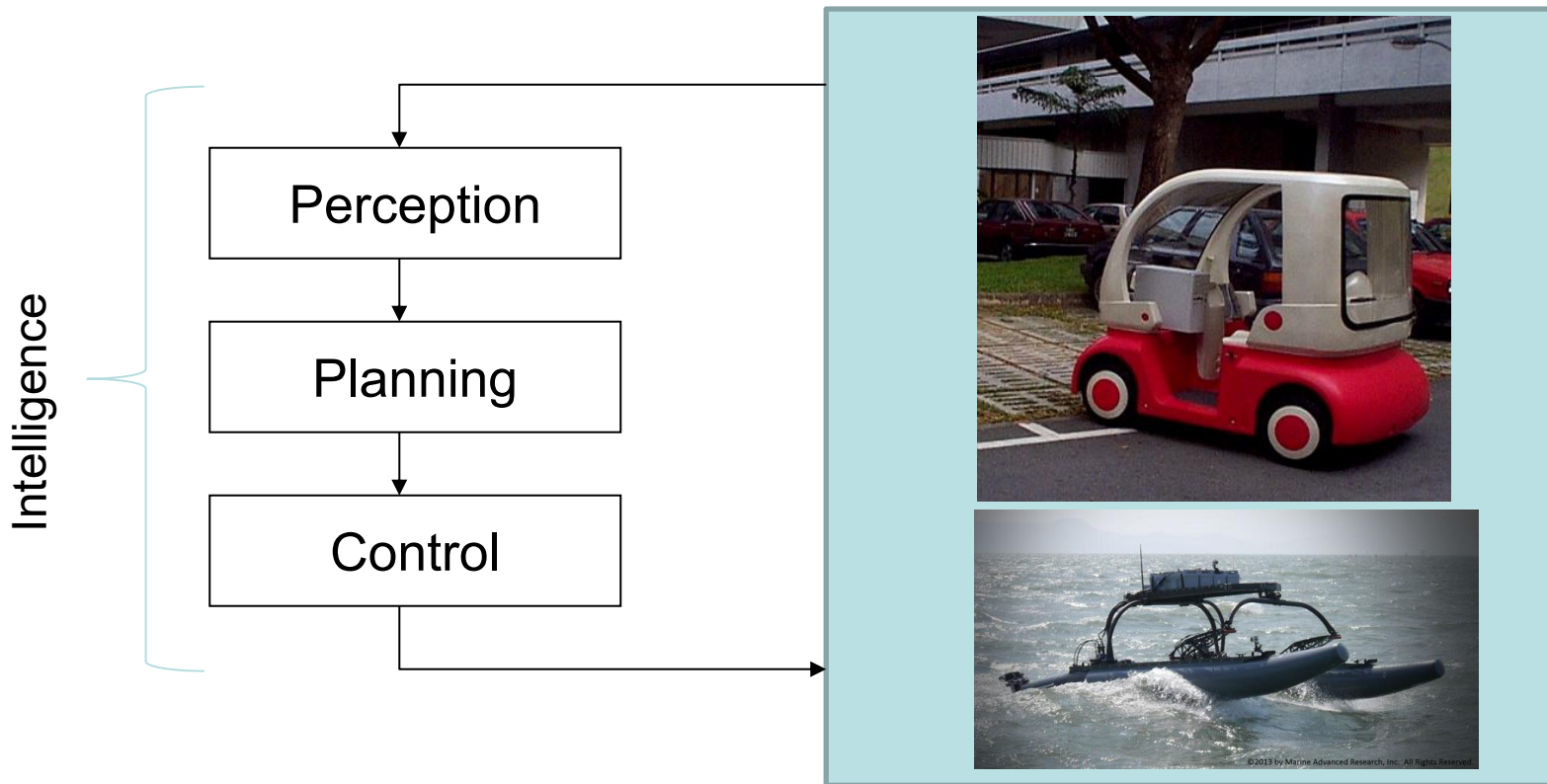


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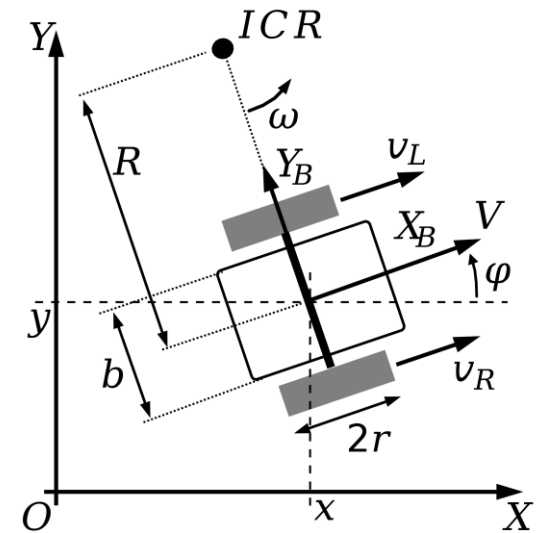
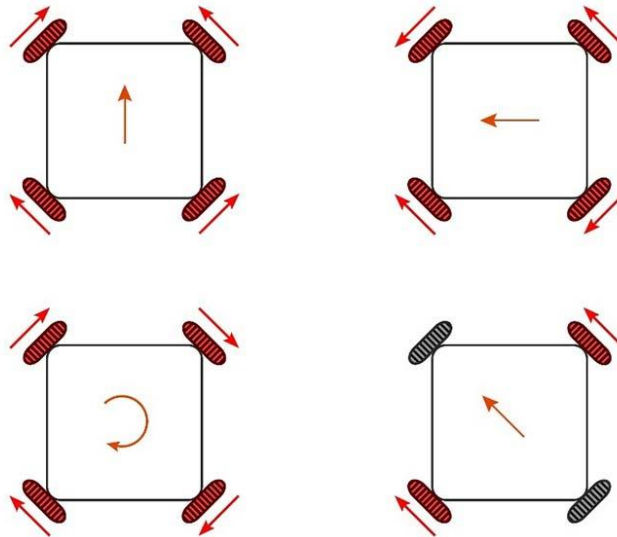
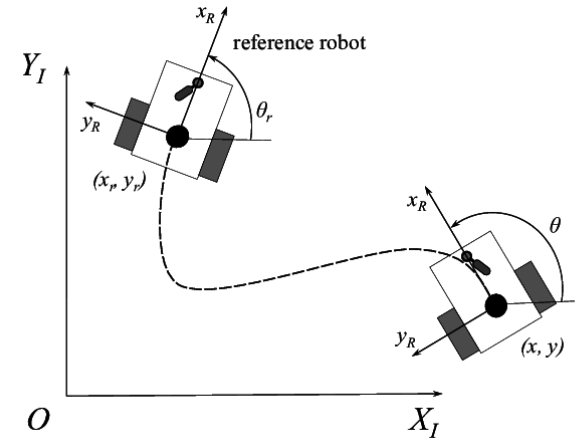


The goal of control is to make the actual motions, in terms of linear and angular movements, to follow the intended trajectories

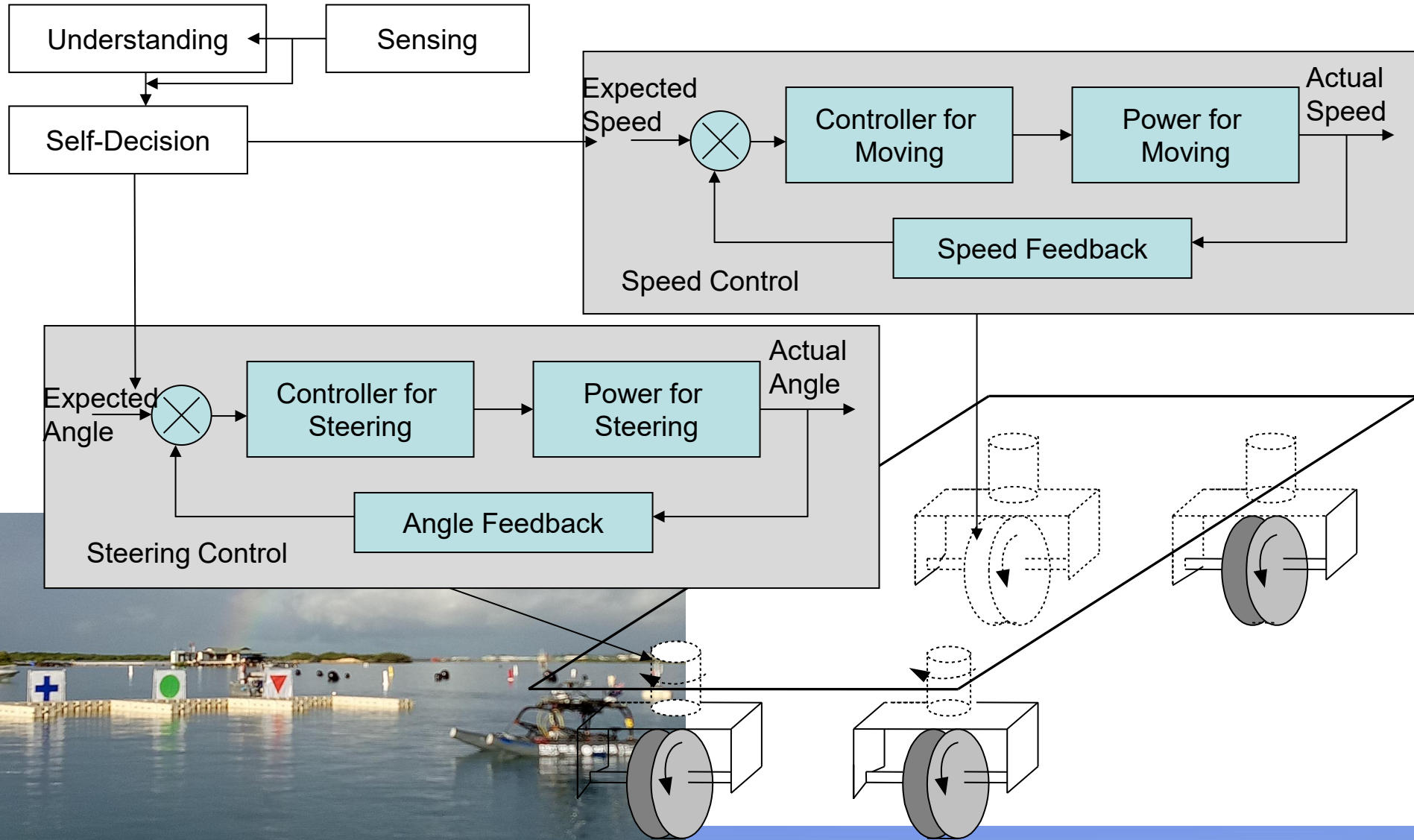


Three Types of Dynamic Platforms

- Car-like Platforms
- Differential-Drive Platforms
- Omni-Directional Platforms



A Car-like Platform Has Two Control Loops ...



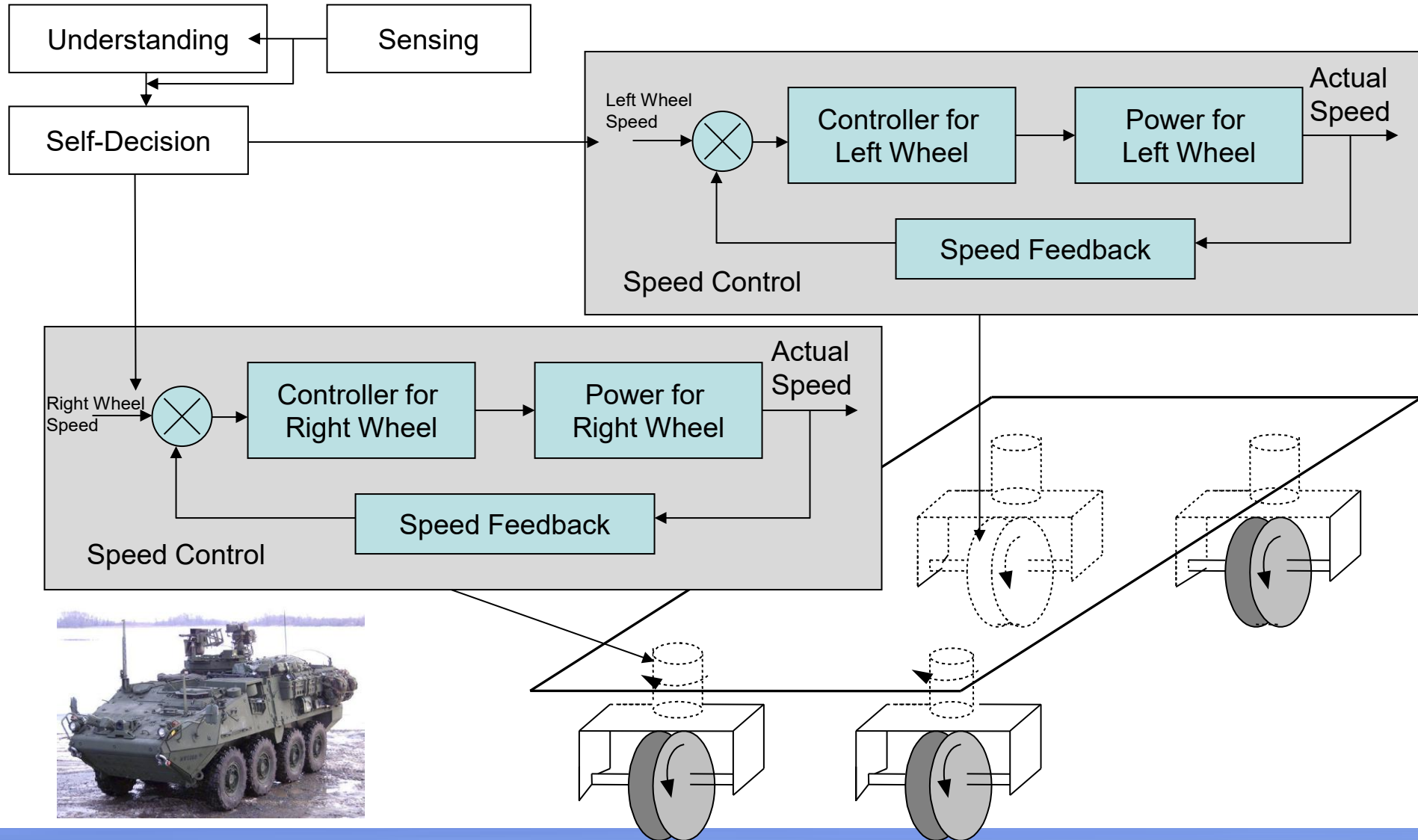
Multiple-mode Control of Car-like Vehicle



Demonstration of Perception, Planning and Control of Car-like Vehicle ...



A Differential-Drive Platform Has Also Two Control Loops ...



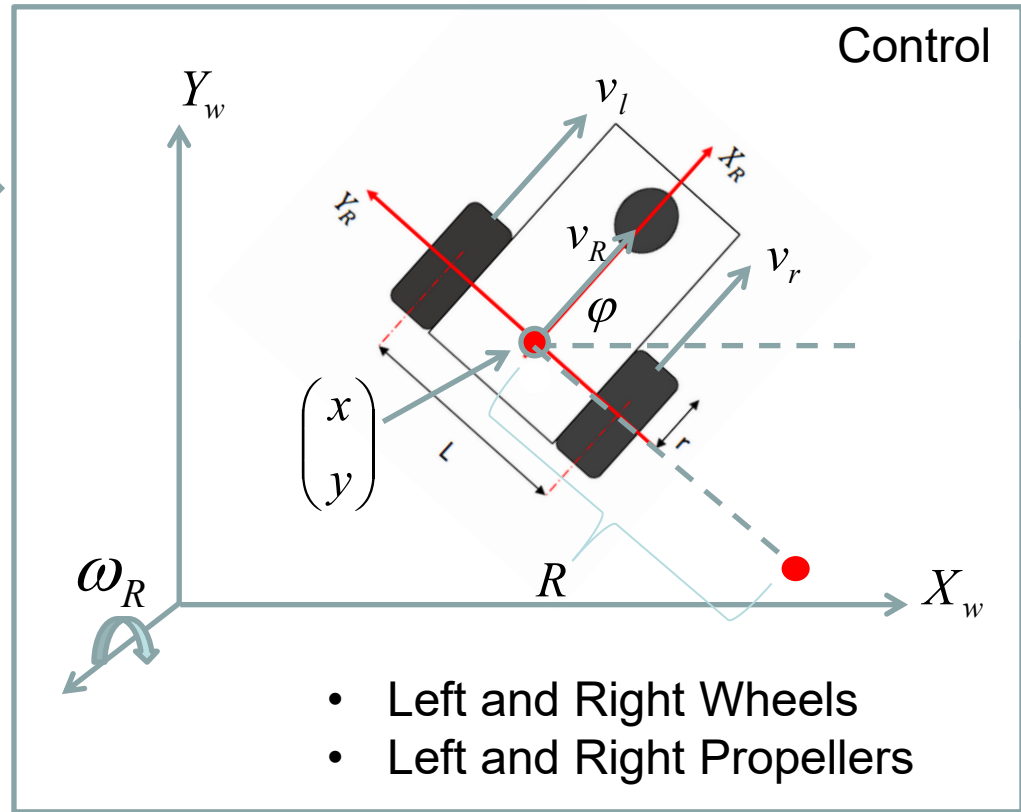
Planning and Control of Differential-Drive Vehicle

Joint Space Planning

$$\begin{cases} v_l = \frac{1}{2}(2v_R - L\omega_R) \\ v_r = \frac{1}{2}(2v_R + L\omega_R) \end{cases}$$

Task Space Planning

$$\begin{cases} \dot{x} = v_R \cos(\phi) \\ \dot{y} = v_R \sin(\phi) \\ \dot{\phi} = \omega_R = \frac{v_R}{R} \end{cases}$$



$$\begin{pmatrix} x \\ y \\ \phi \end{pmatrix}$$

Desired Trajectories in Task Space

$$\begin{pmatrix} x^d \\ y^d \\ \phi^d \end{pmatrix}$$



Task-Space Dynamics of Wheel or Propeller

- Use of State-space Equations in Time Domain:

- Left or right wheel

$$F_{net} = \frac{\tau_{wheel}}{r_{wheel}}$$

- Left or right propeller

$$F_{net} = F_{thrust} - F_{drag}$$

$$F_{net} = m \bullet \ddot{x}$$

$$\ddot{x} = \frac{F_{net}}{m}$$

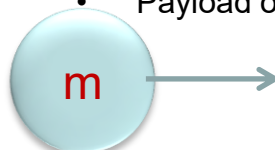
$$\ddot{x} = \frac{F_{net}}{m} = u$$

$$X = \begin{pmatrix} x_1 \\ x_2 \end{pmatrix} = \begin{pmatrix} x \\ \dot{x} \end{pmatrix}$$

$$\ddot{x} = u$$

$$\begin{pmatrix} \dot{x} \\ \ddot{x} \end{pmatrix} = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} x \\ \dot{x} \end{pmatrix} + \begin{pmatrix} 0 \\ 1 \end{pmatrix} u$$

- Payload of wheel
- Payload of propeller



Y

X

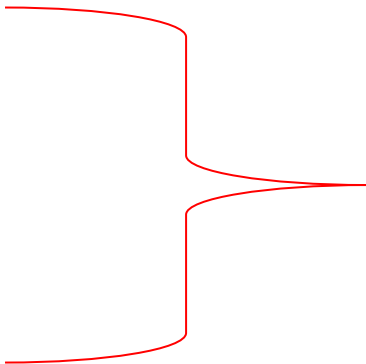
About Eigenvalues and Eigenvectors

$$\begin{aligned}
 A\vec{v} &= \lambda\vec{v} \\
 A\vec{v} - \lambda I\vec{v} &= 0 \\
 (A - \lambda I)\vec{v} &= 0 \\
 \det(A - \lambda I) &= 0
 \end{aligned}$$



$$D = \begin{bmatrix} \lambda_1 & & & \\ & \lambda_2 & & \\ & & \dots & \\ & & & \lambda_n \end{bmatrix}$$

$$V = [v_1 \quad v_2 \quad \dots \quad v_n]$$



$$X(t) = V(t) \times e^{D \times t}$$



$$V^{-1} \times X(t) = e^{D \times t}$$



$$(V^{-1} \dot{X}) = D \times (V^{-1} X)$$



$$\dot{X} = V D V^{-1} X$$



$$\dot{X} = A X$$

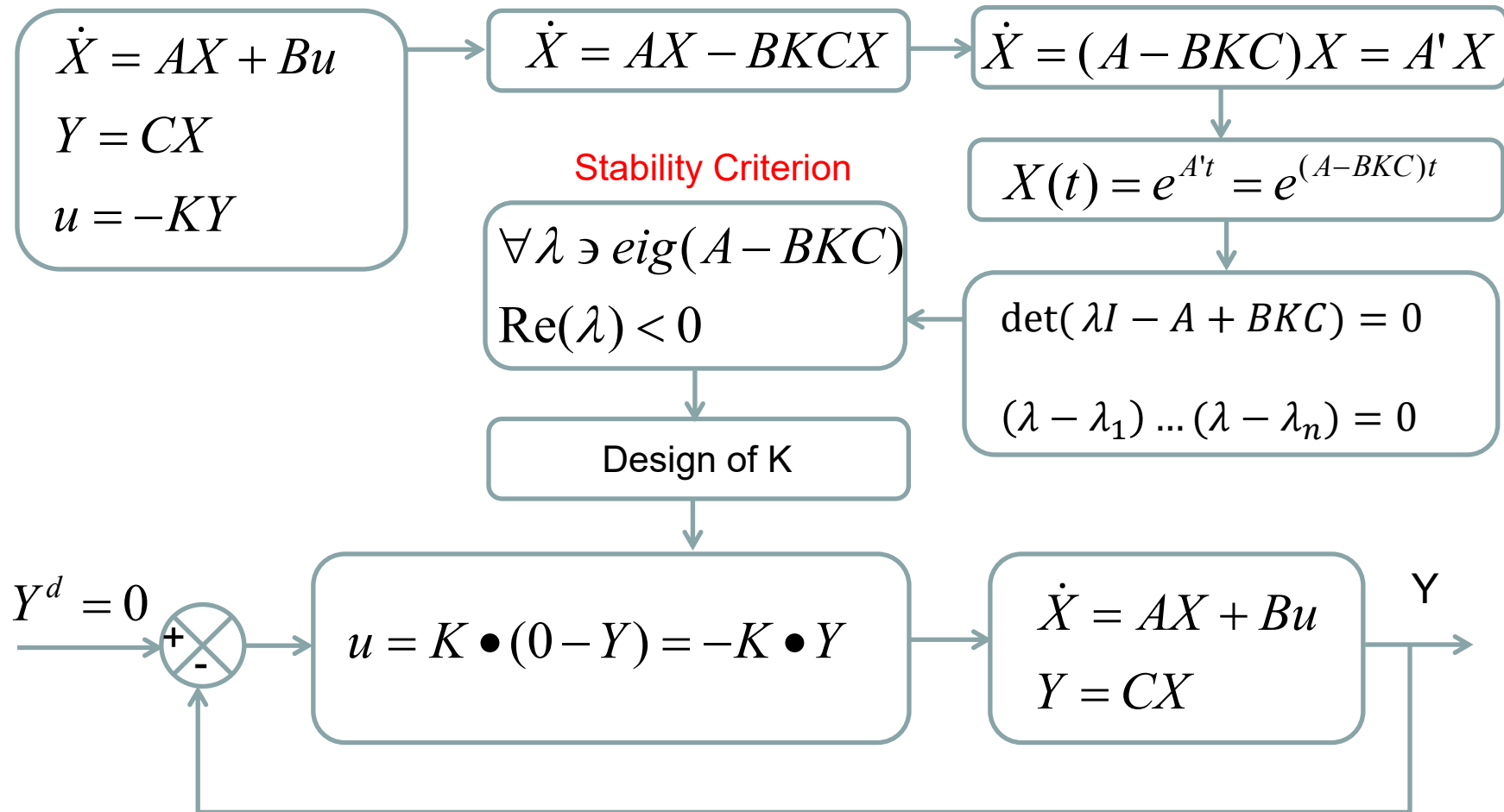


$$A = V \times D \times V^{-1}$$

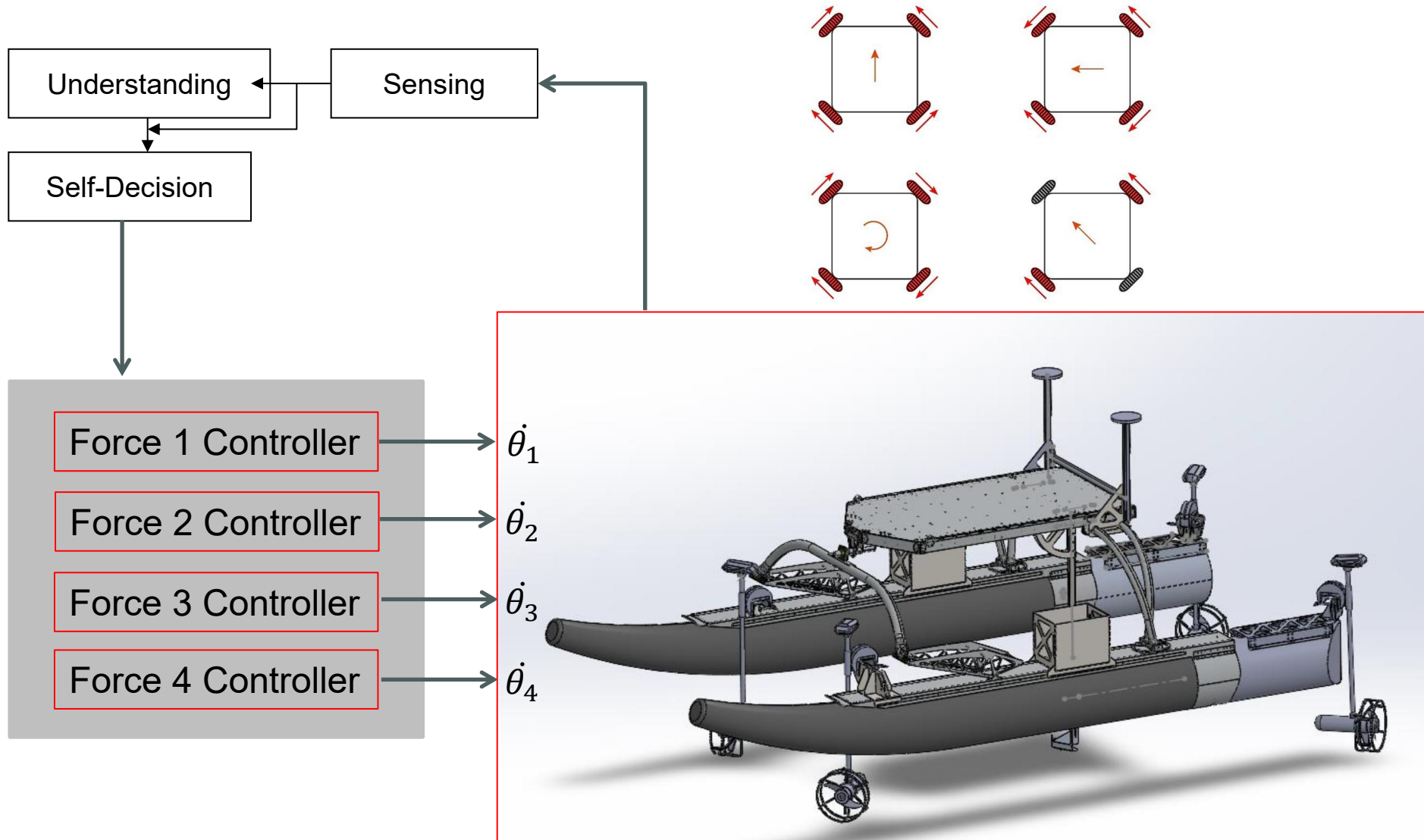
This is called Diagonalization!

Design of Task-Space Control ...

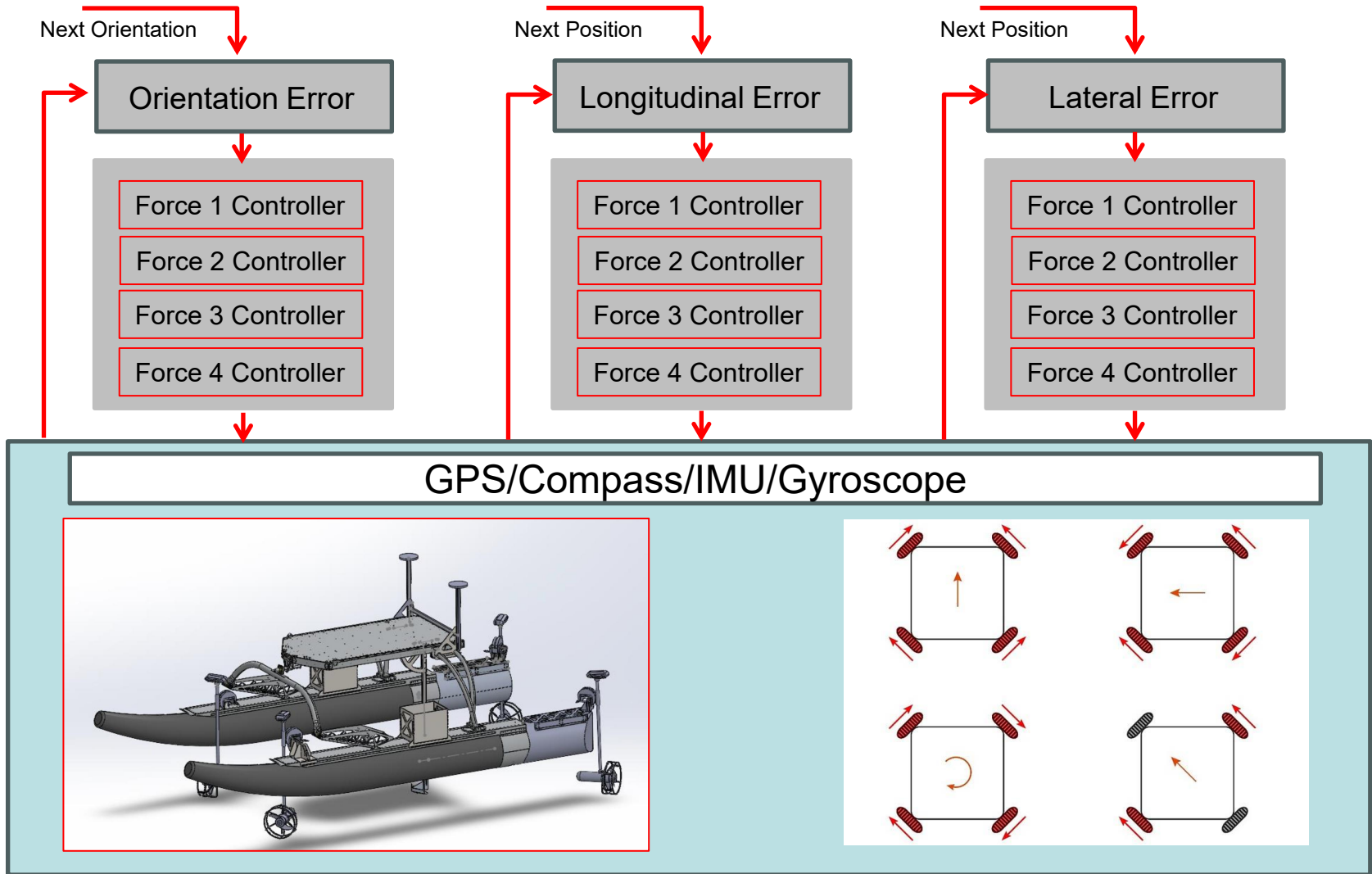
- Use of State-space Equations in Time Domain:



An Omni-Directional Platform May Have Four Control Loops ...

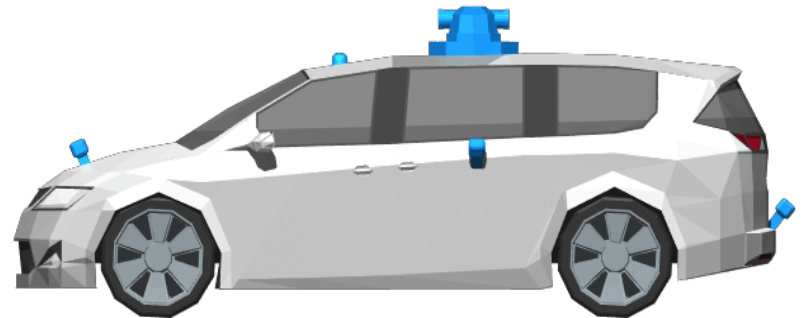


Control Loops of Surface Vehicle

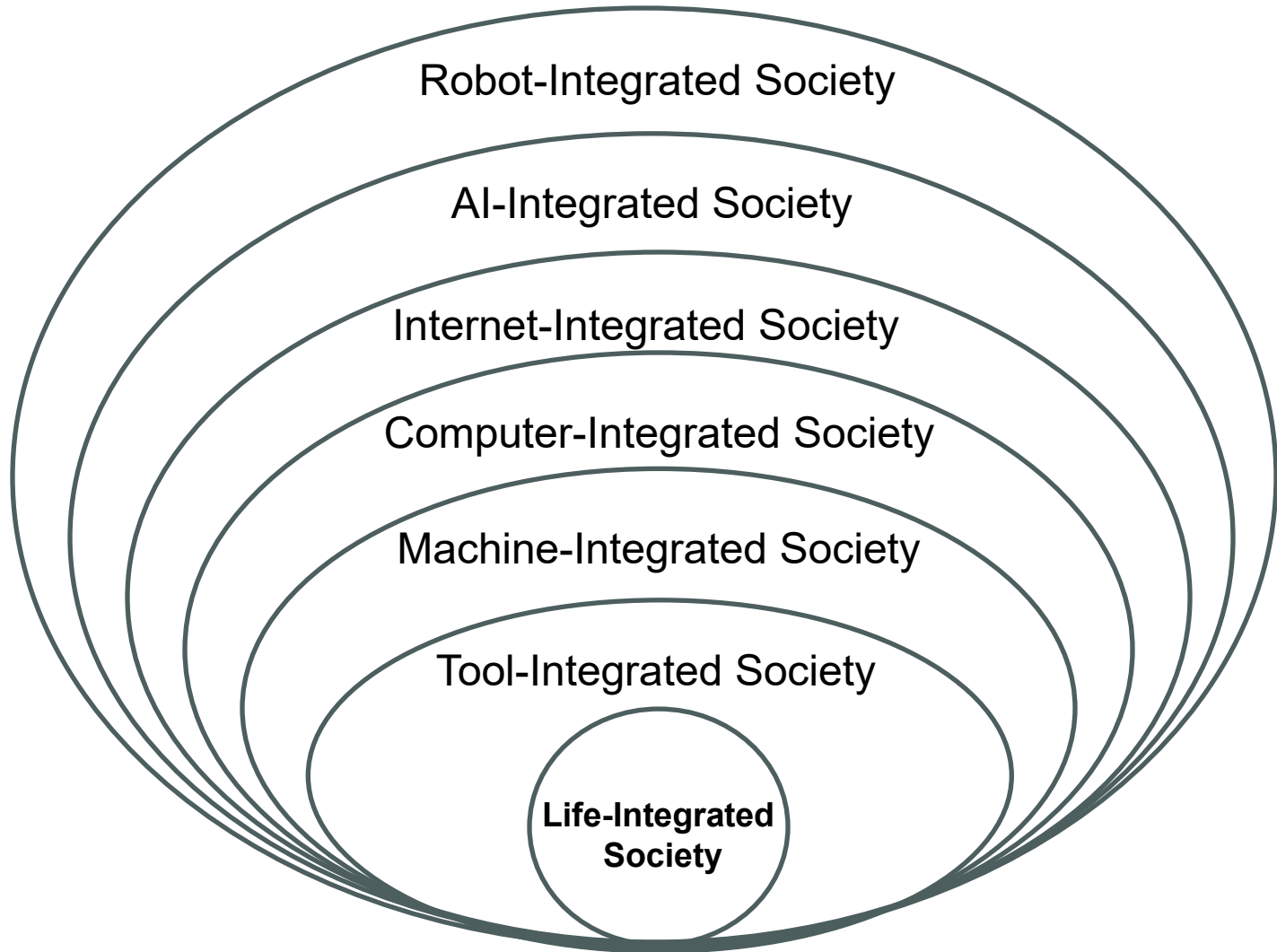


Outline of Today's Talk

- Why to Develop Autonomous Vehicles?
- What is an Autonomous Vehicle?
- What are the Major Initiatives?
- How to Develop Autonomous Vehicles?
 - Key Technologies of Perception
 - Key Technologies of Planning
 - Key Technologies of Control
- **Future Works**



What Will Be Future Trend of Human History?



How to fulfill our missions on Earth, which include: (1) to understand the world, and (2) to improve the world?

Research comes first:

- What is research? What are the 1,2,3 of research?

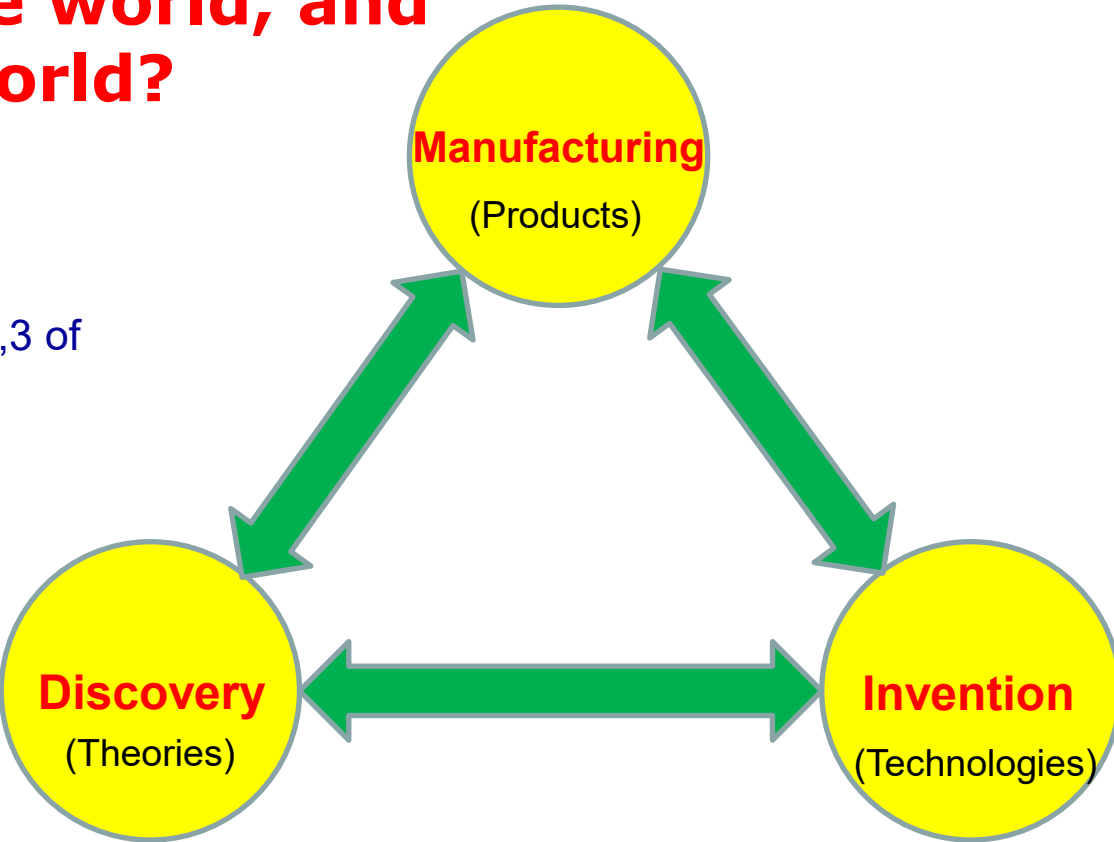
One Objective:

1. Research has one objective which is to create values by finding better ways of solving problems.



Two Driving Forces of Research

1. Scientific Problems
2. Social Needs



Three Outcomes:

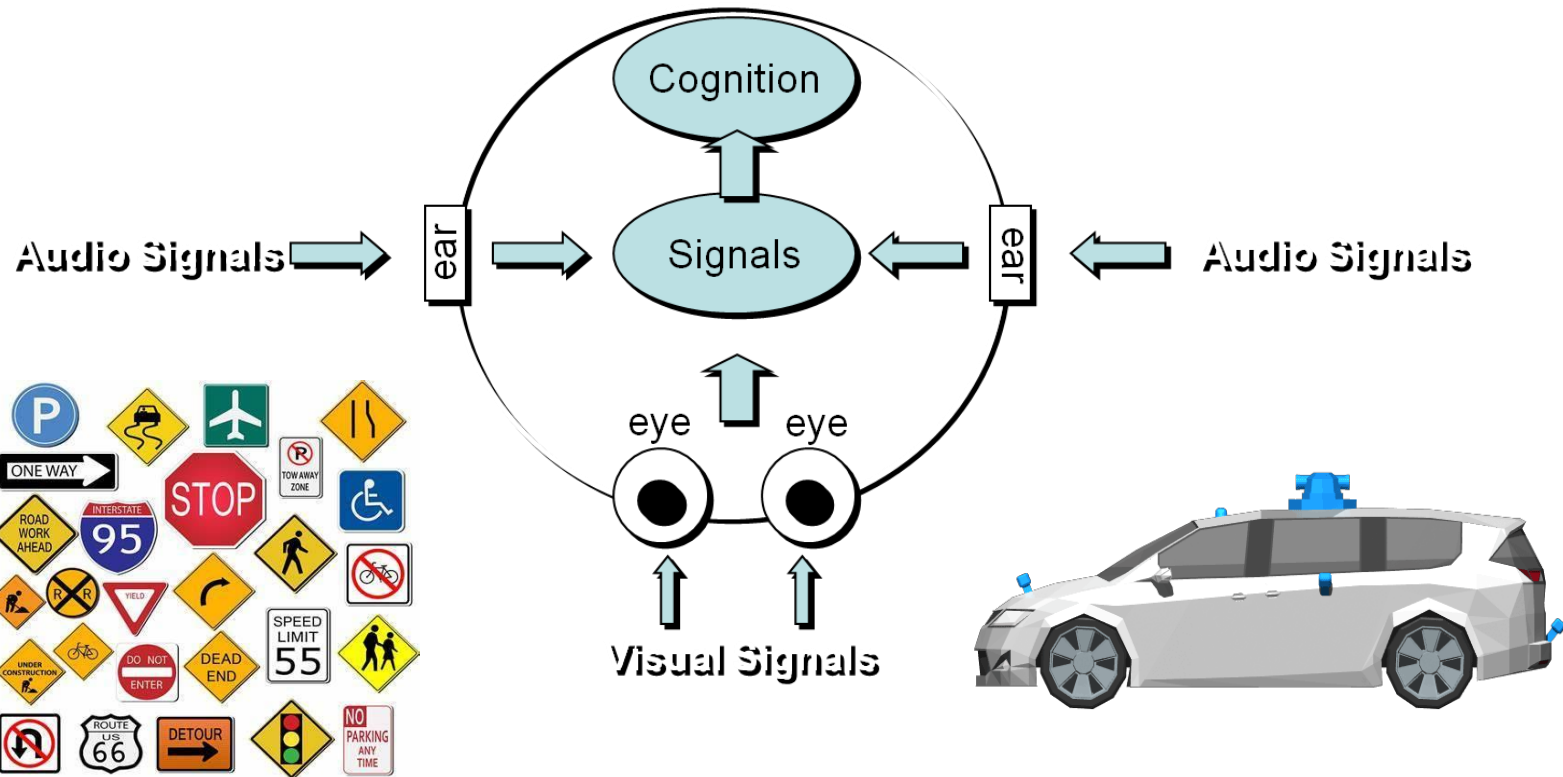
1. Creation of Better Theories
2. Creation of Better Technologies
3. Creation of Better Products



How to design a vehicle's mind?

One of the Last Frontiers in Science: The Discovery of Human Mind's Blueprint.

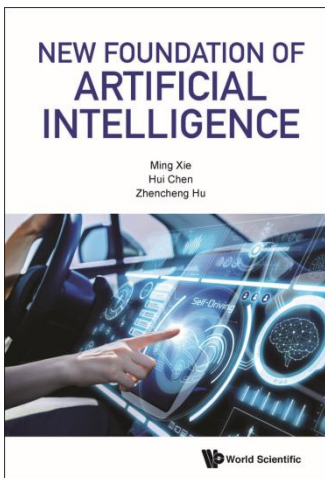
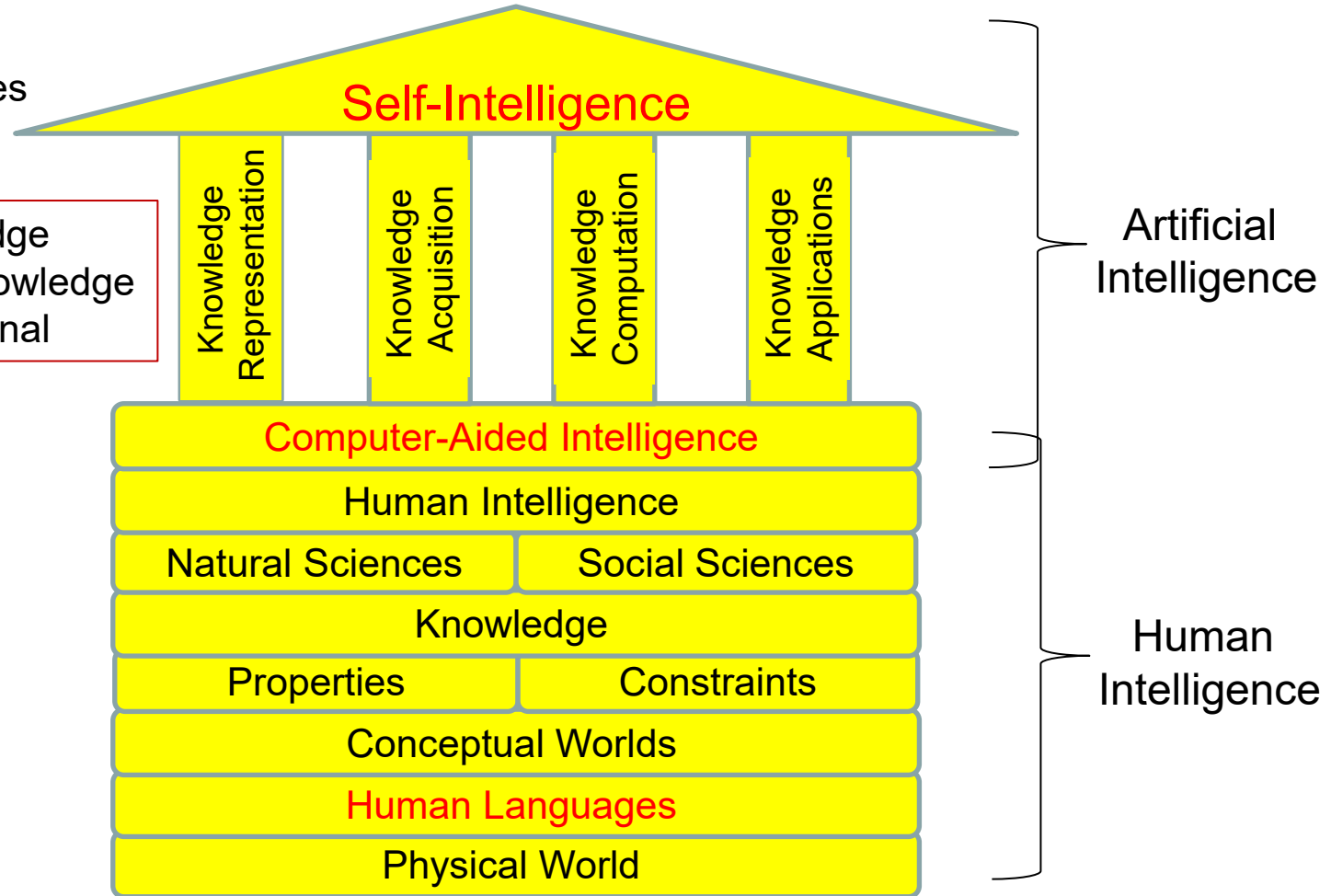
- What are the physical principles behind the transformations from signals to cognitive states of knowing the meanings inside the signals?



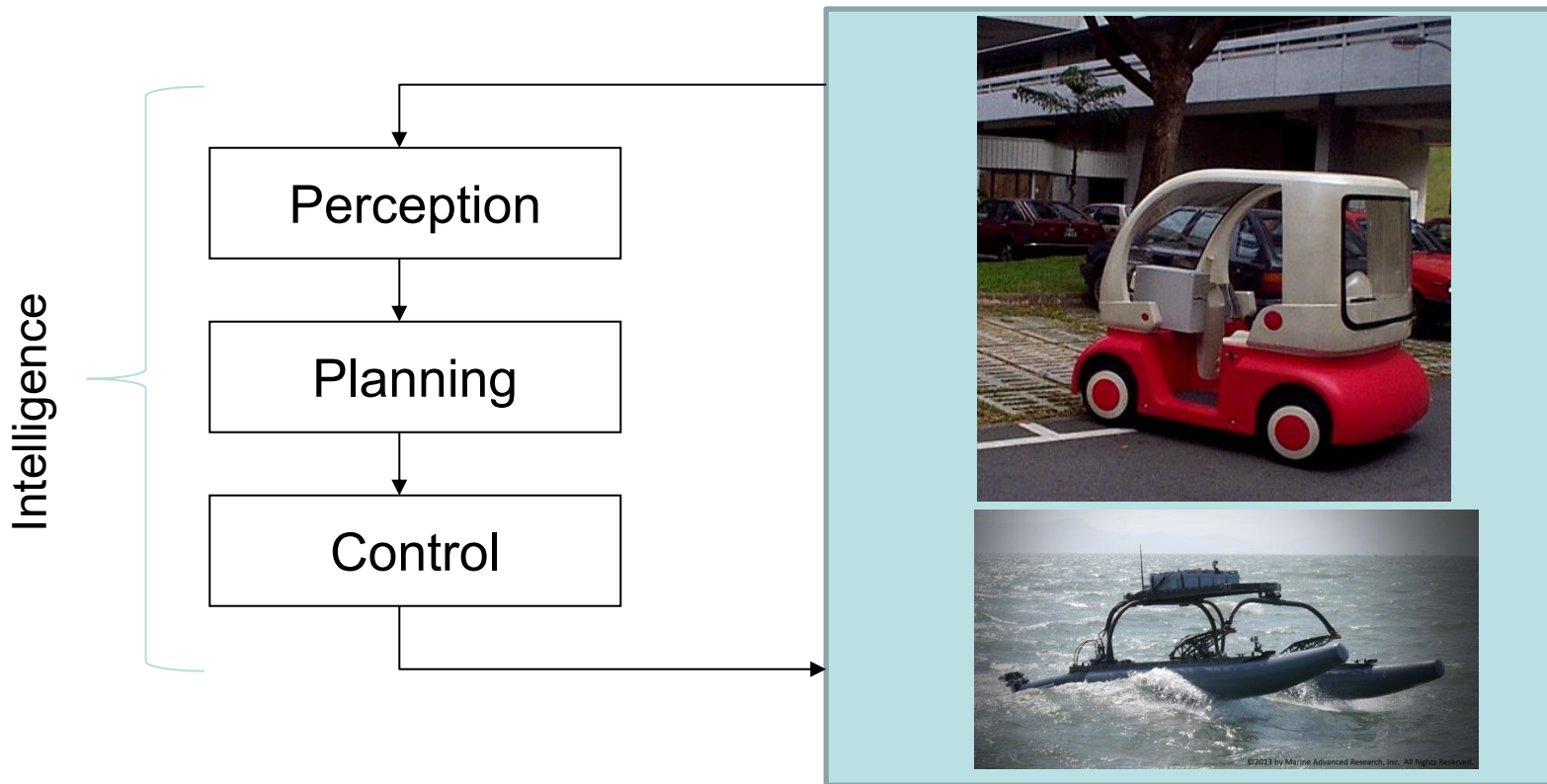
New roadmap toward developing vehicle's self-intelligence ...

- One Tool
- Two Worlds
- Three Intelligences
- Four Pillars

- Signal to Knowledge
- Knowledge to Knowledge
- Knowledge to Signal



Autonomous vehicles are becoming high-speed mobile robots. Automobile industry will become part of robotics industry.

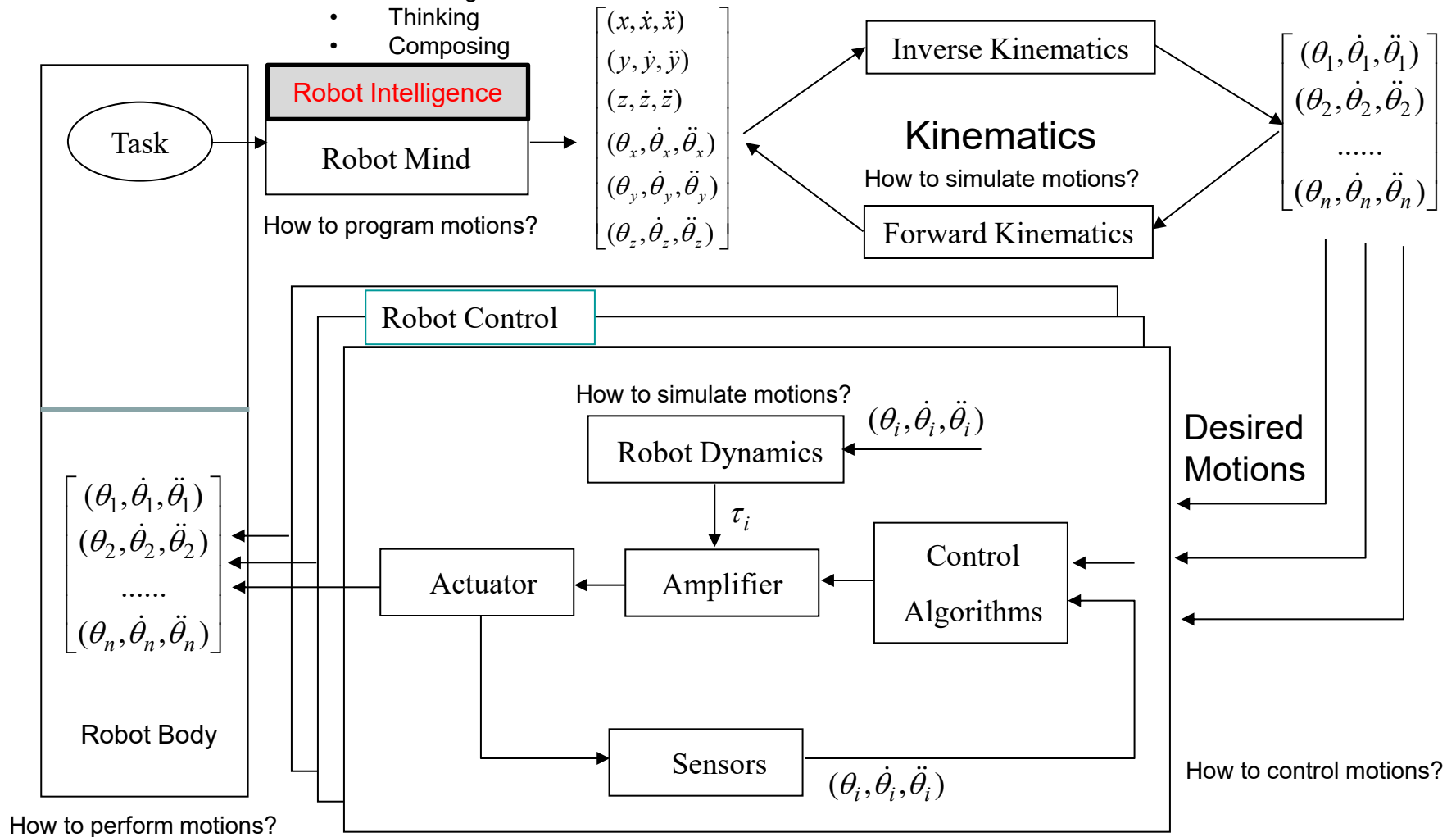


Robotics Will Drive the Development of Vehicle's Self-Intelligence ...

- Talking
- Seeing
- Reading
- Thinking
- Composing

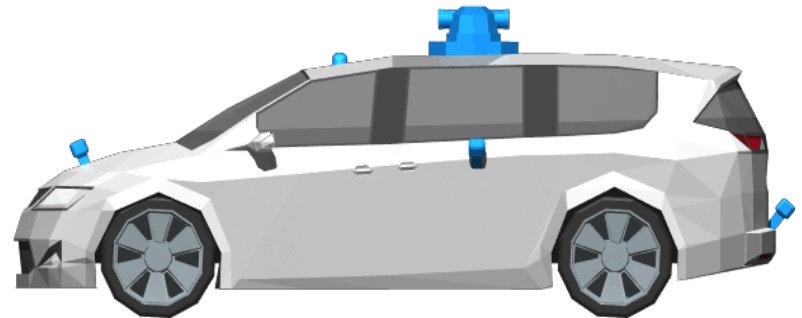
Task Space

Joint Space



Summary of Today's Talk

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- Future Works





**NANYANG
TECHNOLOGICAL
UNIVERSITY**

School of Mechanical & Aerospace Engineering

Design, Machine, Control, Intelligence

Thank You!

Q & A



(Learning, Teaching) <o> (Research, Innovation) <o> (Leadership, Service)