Ph.D. dissertation presentation

: A feasibility study on remote guidance system for untrained animals: turtle and carp by controlling instinctive obstacle avoidance behavior

Mechanical Engineering

Cheol-Hu Kim

Committee : Phill-Seung Lee
Jinwhan Kim
Hyun Chung
Sungho Jo
Daesoo Kim

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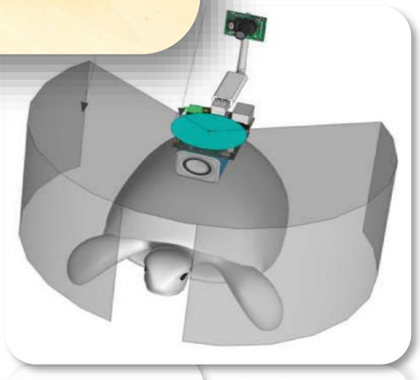
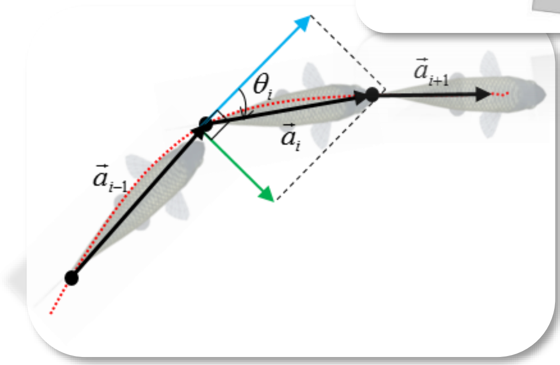
Computational Mechanics
Structural Systems

Contents





Research background

- A “Robot” is **mechanical or virtual artificial agent**, usually an electro-mechanical machine that is guided by a computer program or electronic circuitry.
- Robots have **replaced** humans in performing **repetitive and dangerous tasks**.
- Recent advances in electronics and computer technology have allowed researchers to approach new robot system, **biologically inspired or biomimetic robots has increased**.

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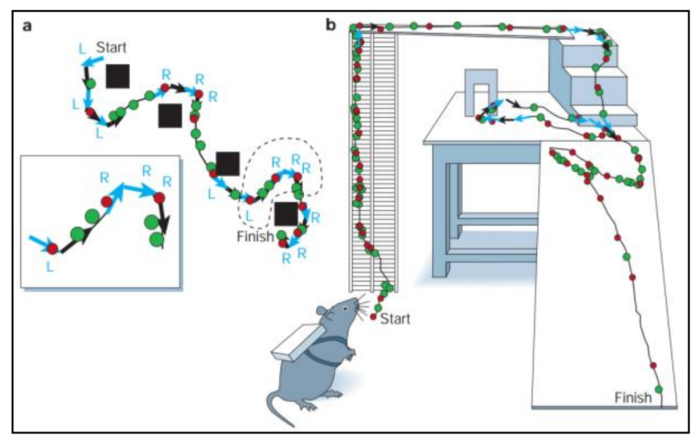
Research background

- However, these systems have not performed as well as expected due to the limitations of mechanical based equipment.

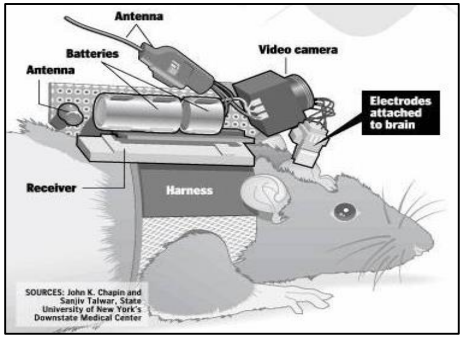
- Some researchers cares deeply about **using animals like as artificial agents**.

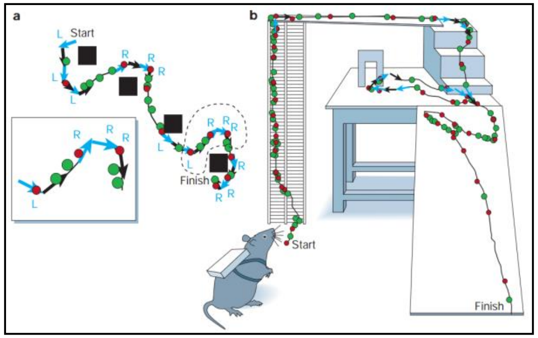
- Is not just relying on training or well trained animal, control the animal agent effectively by applying modern science and technology.



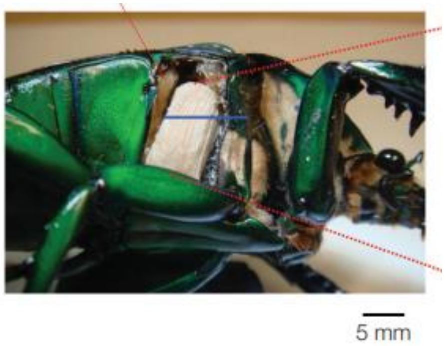
Related research

- Rat navigation guided by remote control
  Talwar, S. K., Xu, S., Hawley, E. S., Weiss, S. a, Moxon, K. a, & Chapin, J. K. (2002). Nature.





- Recent developments in the remote radio control of insect flight
  Sato, H., & Maharbiz, M. M. (2010). Frontiers in neuroscience.



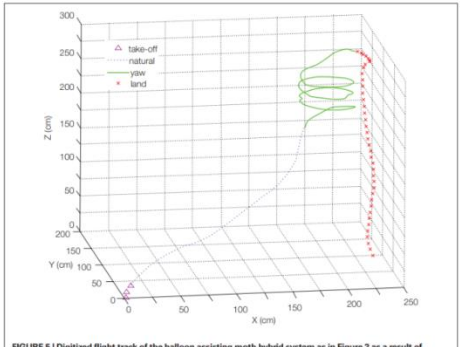


FIGURE 5 | Digitized flight track of the balloon assisting moth hybrid system as in Figure 2 as a result of applied stimulation pulses. Reproduced from Bozkurt et al. (2009b).

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Research background

- Most proposed animal agent systems require a still **well-trained animal** or cause **involuntary behavior** by direct stimulation of the corresponding musculature by an **implanted (invasive) controller**.

- So, we propose the new control system which is **non-invasive**, **using voluntary behavior** and adaptable to **untrained animals.**

Then, how to control?

- Non-invasive & voluntary scheme -> Using external senses (e.g. vision, hearing etc.)
- All animals, including humans, usually act by reaction to stimuli.
- The cause of the response to external stimuli : Instinct or Experience
  - ✓ Instinct : Instinct (or innate behavior) is the **inherent inclination** of a living organism towards a particular complex behavior.
  - ✓ Experience : Experience is the **knowledge or mastery** of an event or subject gained through involvement in or exposure to it. In our case, **learning or training (shaping) is essential**. But, it could lead to the desired certain actions.
- Firstly, we choose the '**Instinct**' that **occurs quickly and doesn't needs shaping**.
- Main instinct of animals (orientation; taxis) [1]

: *Klinotaxis (굴곡주성), Tropotaxis (전향주성), Telotaxis (목표주성), Menotaxis (보류주성)*

- Based on these core instinct, animals react to external stimuli.

[1] Tinbergen, N. (1951). The study of instinct.

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Target instinct behavior

- **"Escape behavior"**

  (escape response / escape reflex)

- Escape behavior induces the operant responses that cause the **animal to move away from** an ongoing **punishing** or **obstructing stimulus**.

- Through the interaction of various core instincts, this behavior evoke by a external stimulus.

- By evoke this instinct behavior through the specific stimulation (such as obstruction), we could guide animal's moving route.

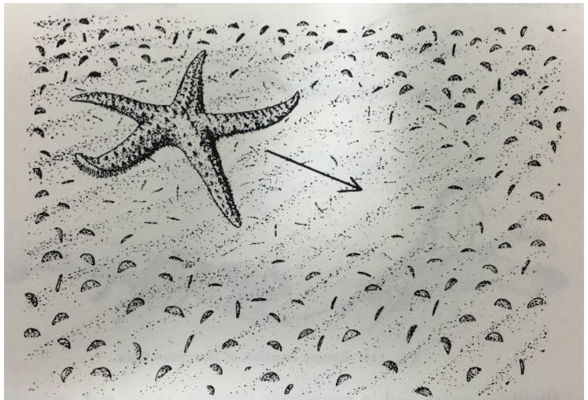

FIG. 115. Sand-dollars and starfish. Arrow indicates weak tidal current. Further explanation in the text.

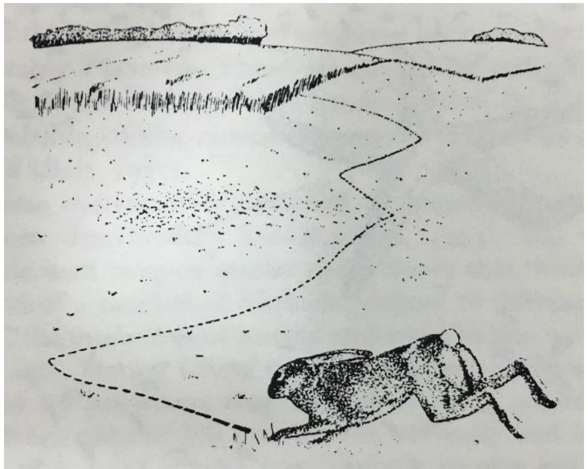

FIG. 116. Escape reaction of European hare.

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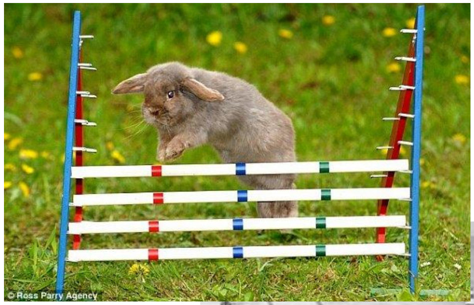
Obstacle Avoidance

- In particular, a reactive behavior connected with bodily protection is **essential** and **must occur quickly**, and it must be evoked, mediated, and directed in a consistent manner by a stimulus.



- This behavior is a kind of expression of an escape instinctive behavior. (**move away from an obstructing stimulus**)

- Especially, **in robotics**, obstacle avoidance is the task of satisfying some control objective subject to **non-intersection or non-collision position constraints**.

- **In our research, we have observed a <u>consistent pattern of an animal</u>'s movement trajectory utilizing the innate instinctive behavior of <u>obstacle avoidance</u>, and we propose this as a <u>animal movement guidance scheme</u>.**

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Idea

- A behavior is a reaction to a stimulus

stimulus → **Programmed AI** → response

Programmed task & attainment → **Programmed AI**

Idea

We can control the response term (system output)

- A behavior is a reaction to a stimulus

stimulus → Instinct and Experience → response

Control the stimulus (system Input)

Modeling the behavioral pattern & way of thinking

Programmed task & attainment

Target animal: Turtle

Red-eared slider (*Trachemys scripta elegans*)

- Living in various types of habitats on **land and in water**
- Easy to detect their movement
- Easy to attach devices
- Four turtles (average length = 15 cm) were grown indoors in laboratories

- **Published on PLoS One journal. (IF. 3.73, April 17, 2013)**
- **Submitted to Journal of Bionic Engineering (Revision)**

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Characteristics of turtle

- Senses : Vision, Auditory, Olfactory (taste) and Tactus
- Especially, it has **superior visual sense** (classify color in visible rays also feeders). [2]
- In particular, there are earlier work on the observation that hatchling sea **turtles recognize a white light source as an open space and so move toward it** [3, 4].
- So, we first conducted experiments to investigate in detail the turtle's obstacle avoidance behavior based on above characteristics of turtle.

[2] Arnold K, Neumeyer C (1987) Wavelength discrimination in the turtle Pseudemys scripta elegans. Vision Res 27: 1501–1511.
[3] Verheijen FJ, Wildschut JT (1973) The photic orientation of hatchling sea turtles during wate finding behavior. Netherlands Journal of Sea Research 7: 53–67.
[4] Witherington BE, Bjorndal KA (1990) Influences of Artificial Lighting on the Seaward Orientation of Hatchling Loggerhead Turtles Caretta caretta. Biol Conserv 55: 139–149.

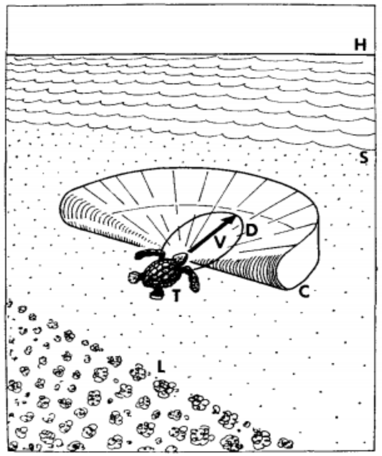
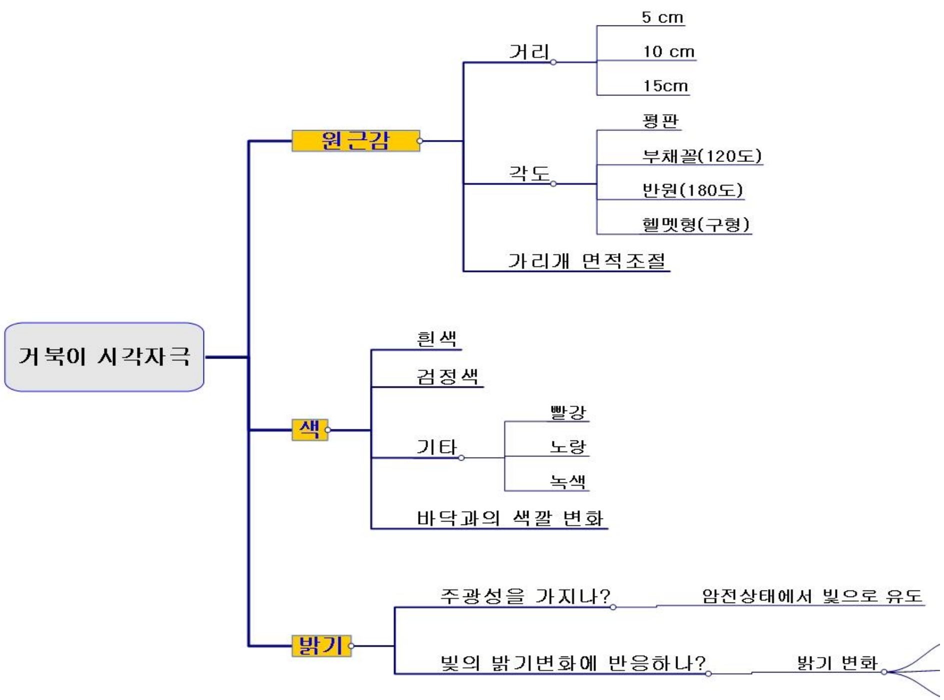
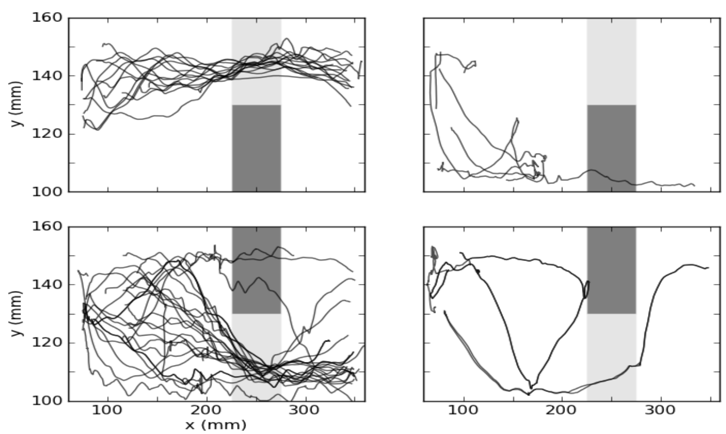
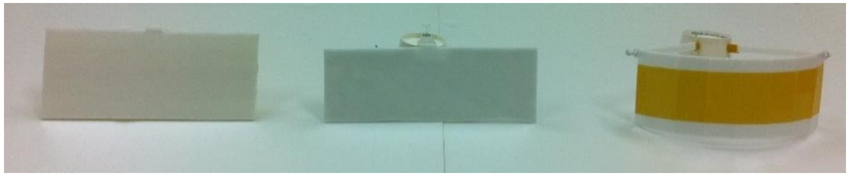


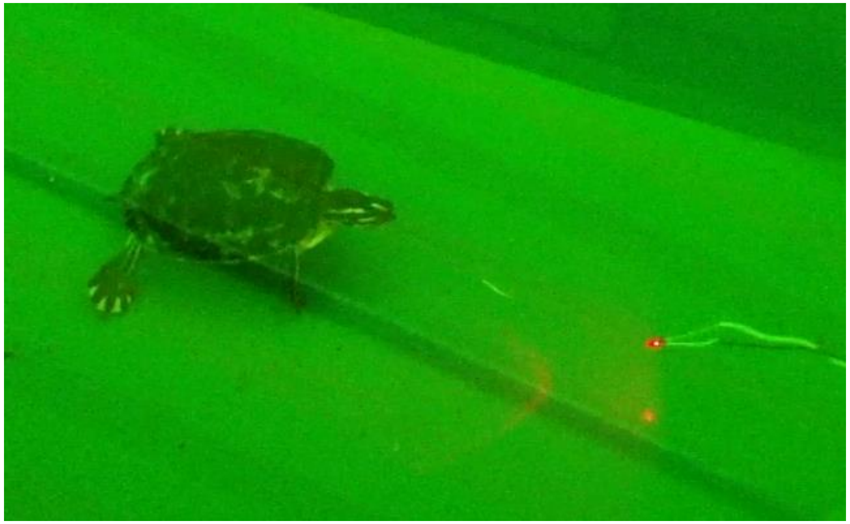
Fig.5. Hypothetical orientation mechanism used during water finding behaviour; H open horizon, S surf line, T hatchling turtle, C input cone, D horizontal brightness distribution as measured via input cone C, V major brightness vector of distribution D, L dark land masses.

Preliminary experimentation

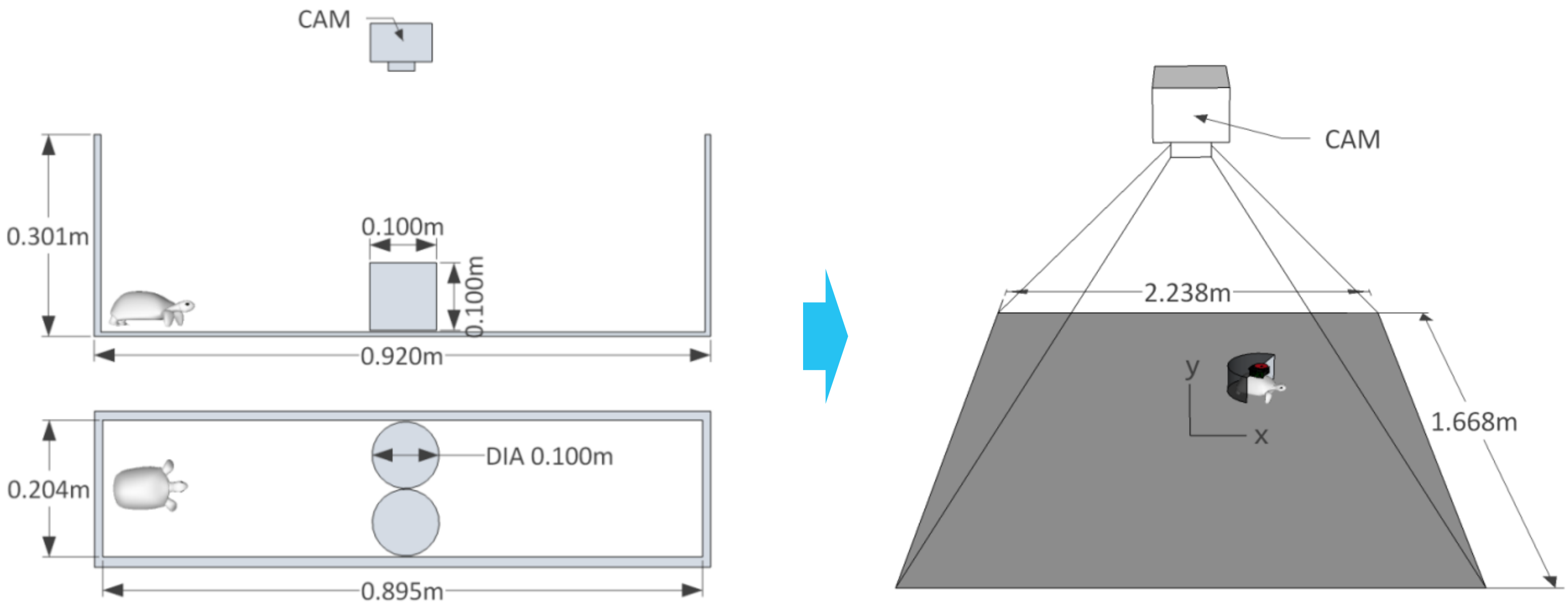






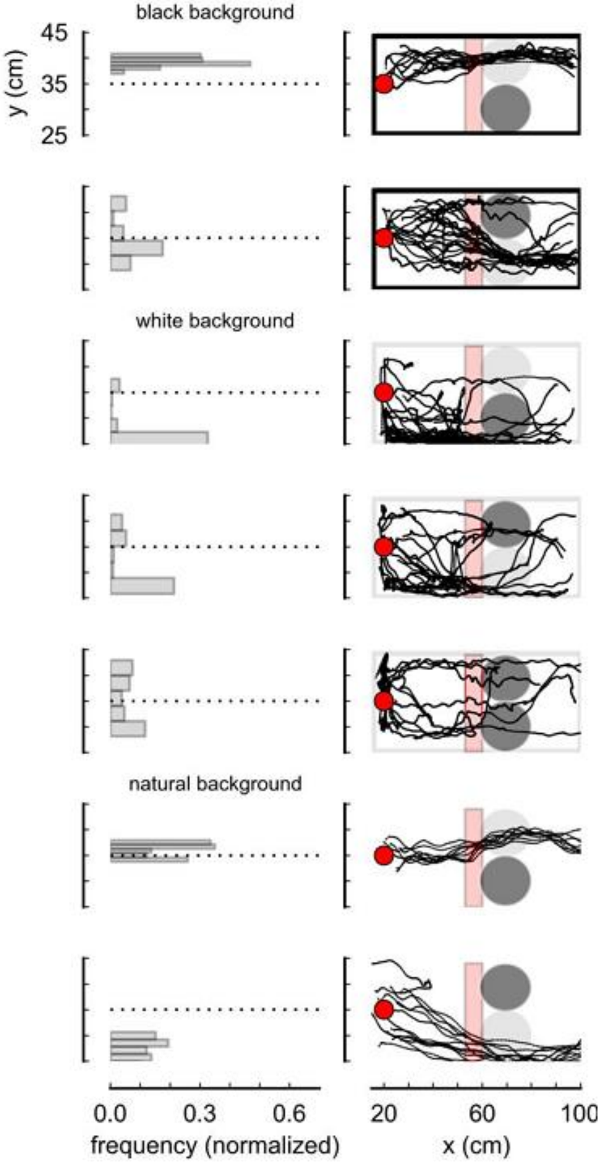


Method & Apparatus



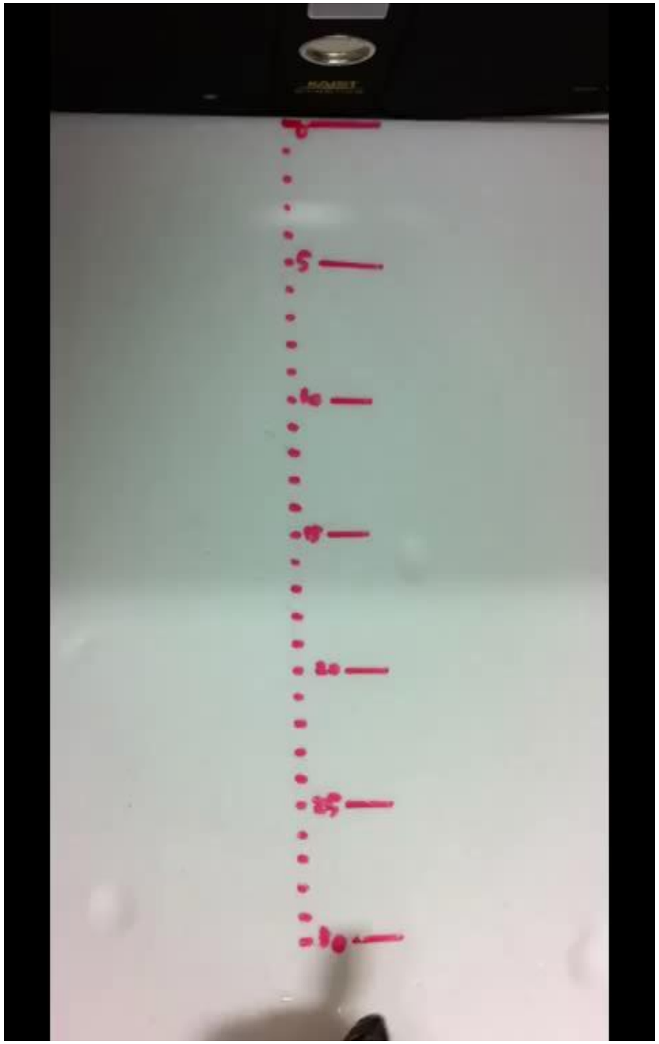
- Type of stimuli
  - ✓ Closed loop stimuli (feedback O, 비지속적 자극)
  - ✓ Open loop stimuli (feedback X, 지속적 자극)

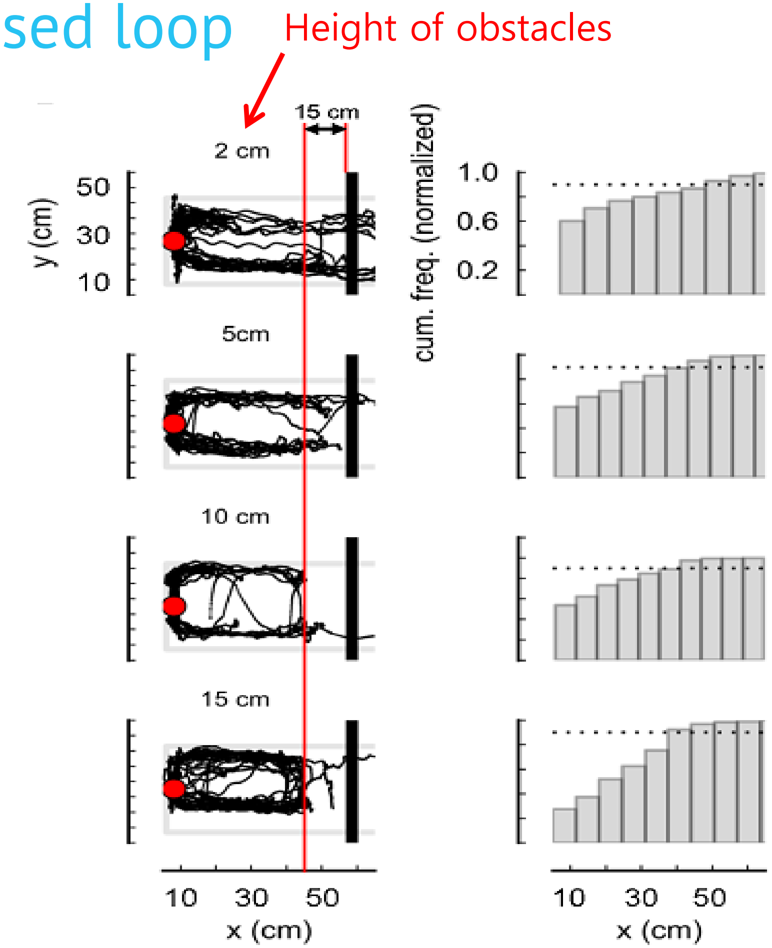
Visual Recognition of Obstacles - Closed loop



- Color Tracking System using MATLAB (able to tracking particular color patch)
- The movement trajectories were tracked after turtles (red circles) were initially placed 50 cm in front of obstacles.

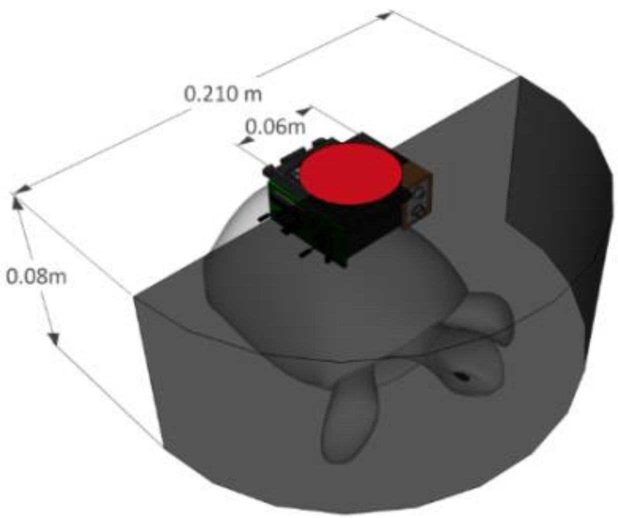
Obstacle Recognition Distance - Closed loop

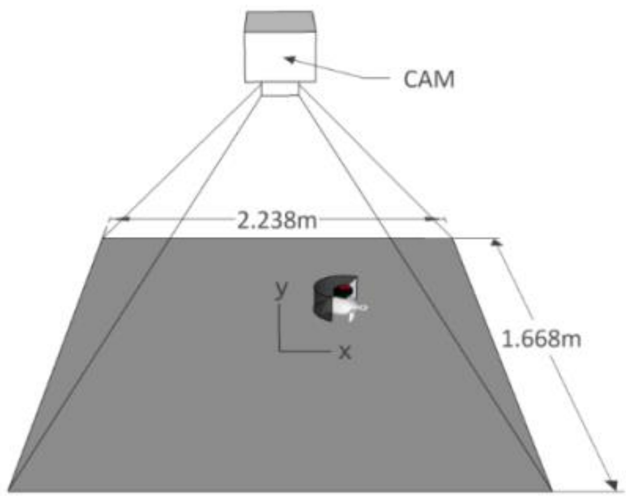


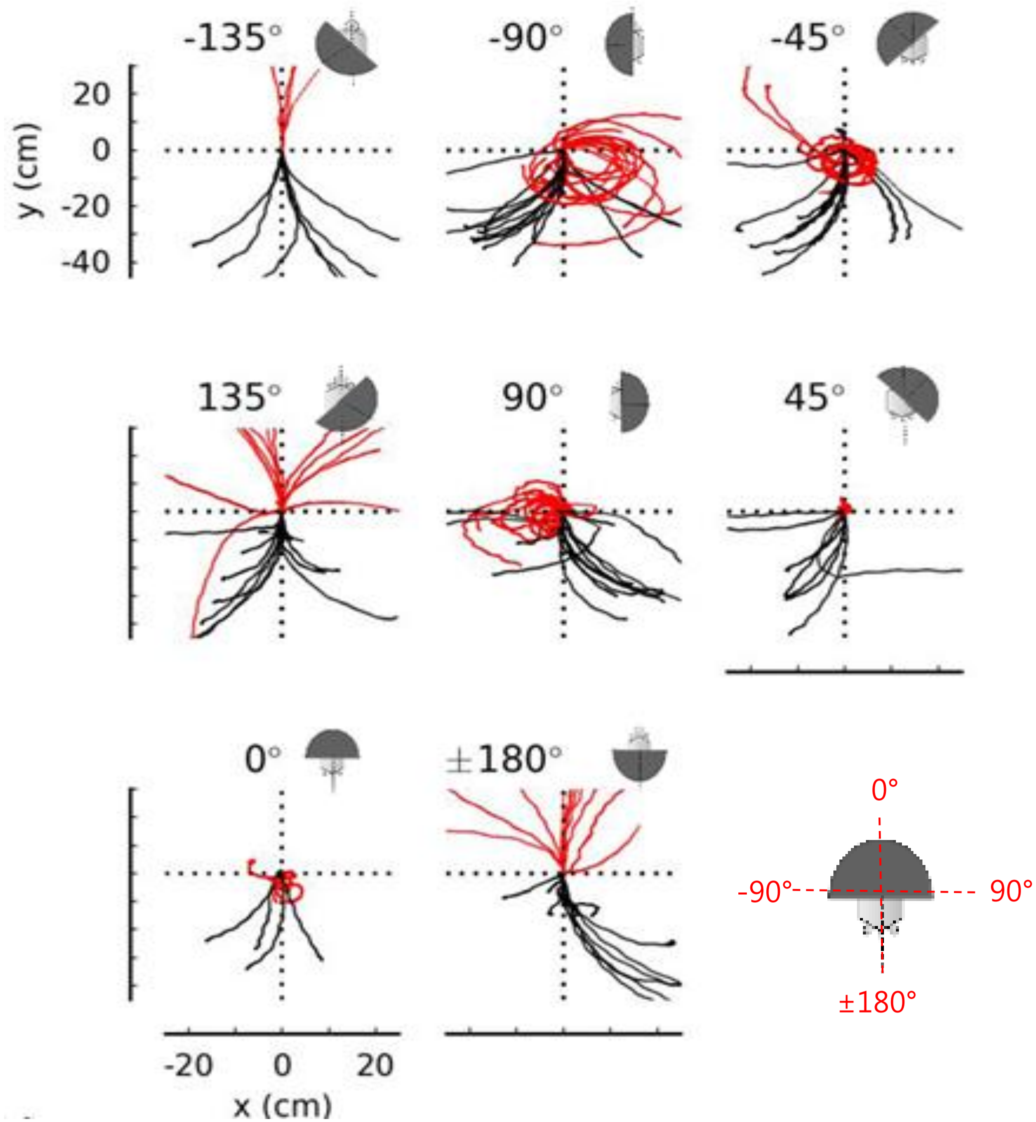


- Turtles were initially located 15 cm (marked by red circles at mid-carapace) in front of a black obstacle wall.

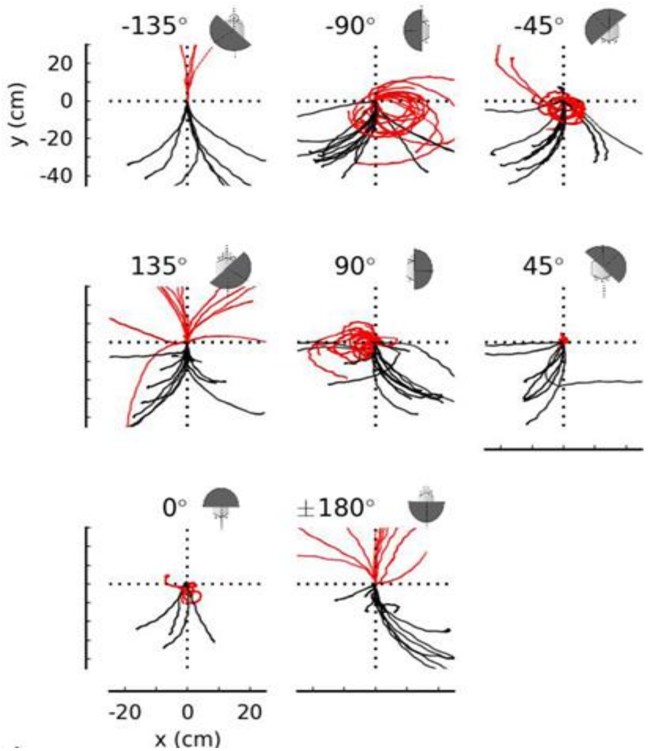
Visually Planned Obstacle Avoidance - Open loop

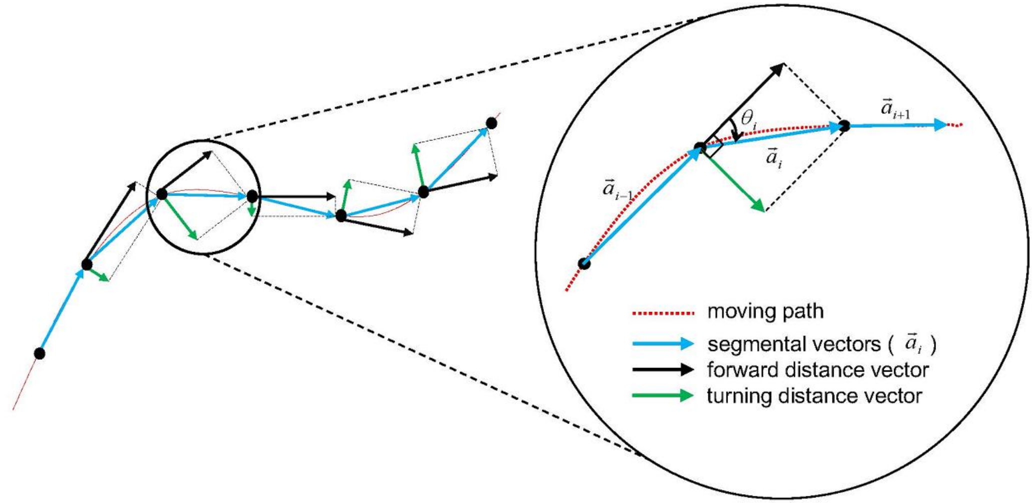






Visually Planned Obstacle Avoidance - Turning Distance



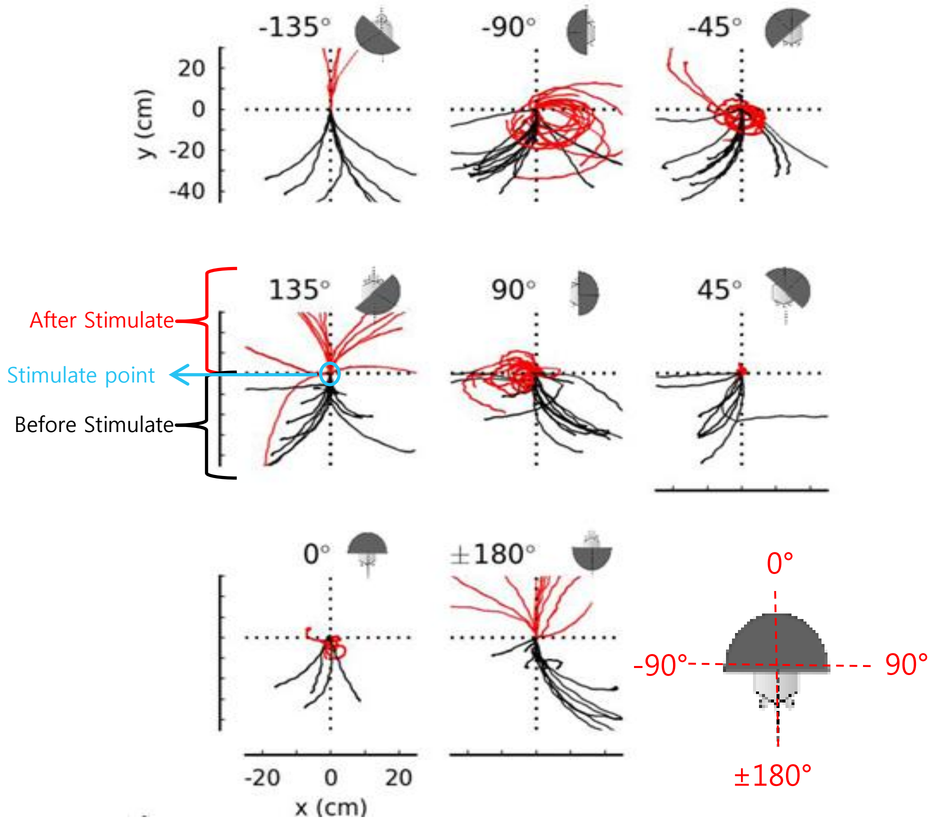


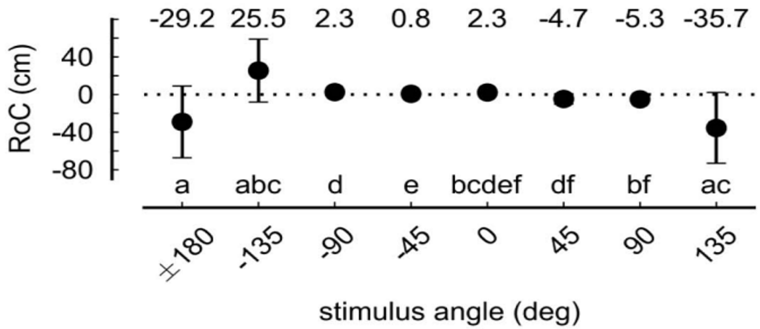
$$\mathrm{ATV} = \frac{\mathrm{TD}}{(\text{total travel time})} \quad \text{with} \quad \mathrm{TD} = \sum_{i=1}^{n} |\vec{a_i}| \sin\theta_i$$

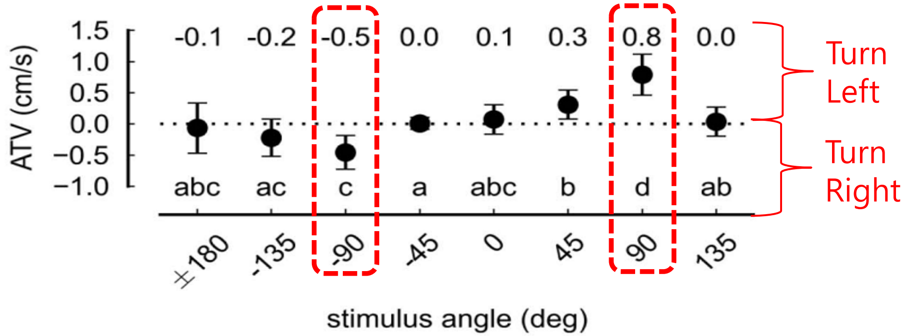
- RoC?
- Angular Velocity?
- These measures does not explain our desire exactly.

- We introduced the concept of **Average Turning Velocity (ATV)** to measure the amount of displacement or shift from the turtle's previous heading per unit of time.

Visually Planned Obstacle Avoidance - Data statistical processing



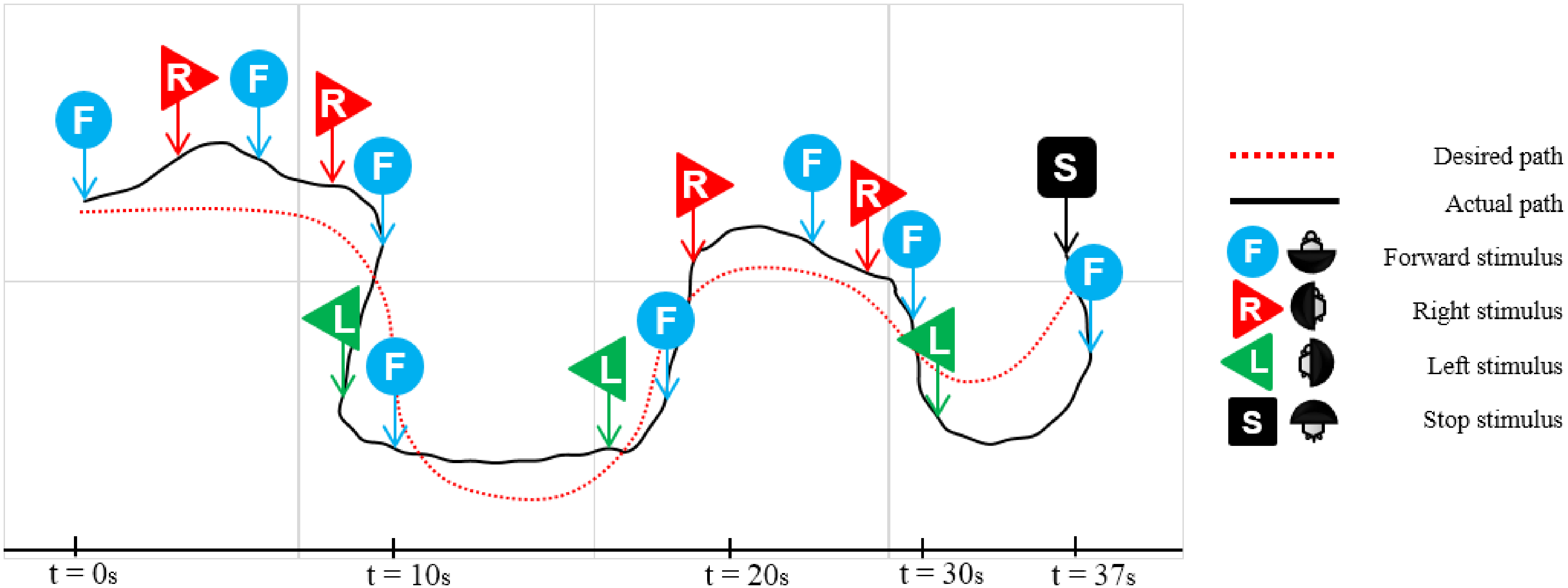




- Each movement trajectory was translated to place the location at which the stimulus was given at the origin, and then rotated so that its tangential line at that location coincides with the y-axis.
- The radii of curvature (RoC) of the red trajectories are plotted by mean and standard deviation. The average turning velocities (ATV) of the trajectories are plotted and analyzed as described for the RoC.

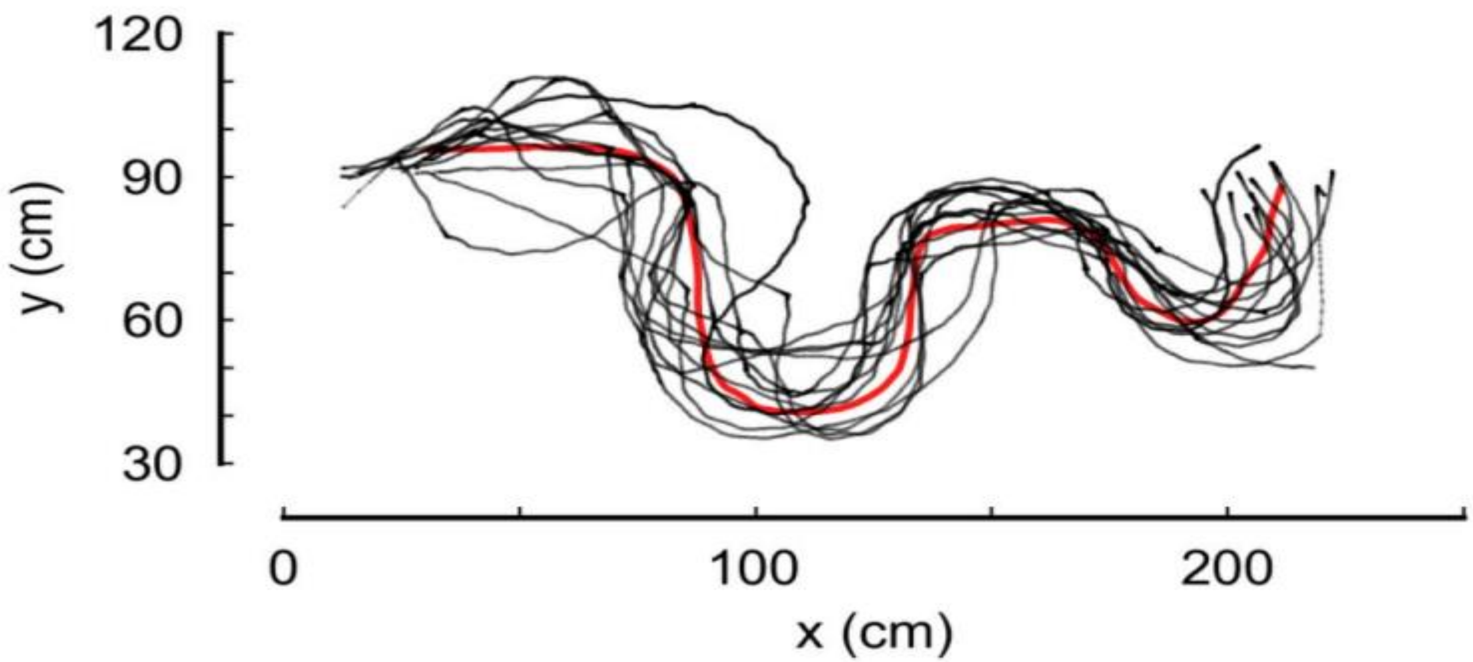
Controlling Turtle's Walking Path

Controlling Turtle's Walking Path



- Examples of guided turtle navigation using the embedded control system to block the turtle's view. Each arrow indicates positions at which forward (F), stop (S), right (R) and left (L) directional stimuli were issued.

Controlling Turtle’s Walking Path



- Turtle movement was controlled by alternately providing forward, right, left and stop stimuli causing obstacle avoidance. The desired (red) and actual (black) paths of the turtles are plotted.

Go outside!

- In indoor experimental condition, we could easily control the 'control variables'.

- **We should check our scheme is also valid in outdoor condition which has various variables.**

- To implement outdoor experiment, our stimulation device should be modified.
  - ✓ Telecommunication
  - ✓ Positioning system
  - ✓ Stimulation cylinder

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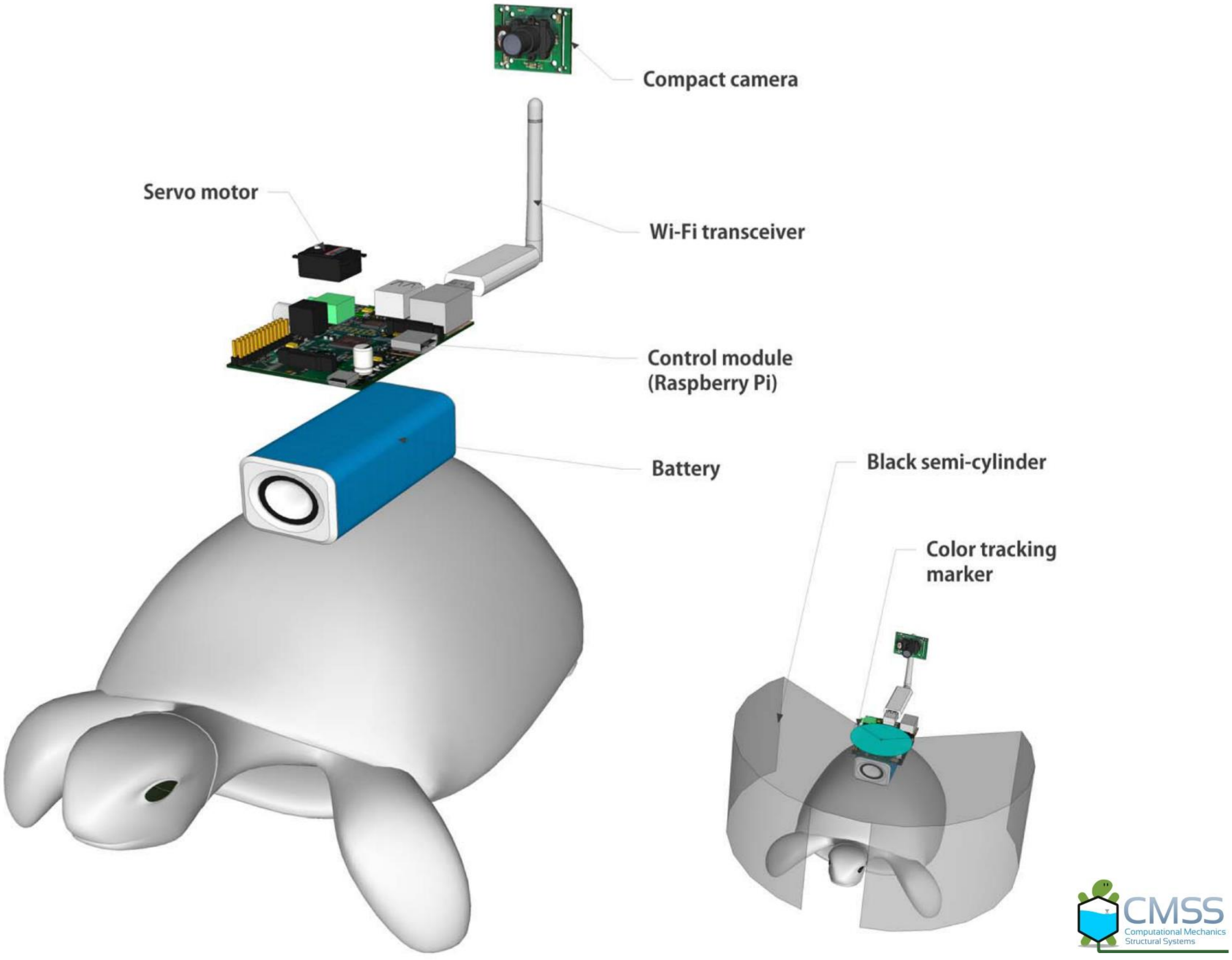
Compact camera
Servo motor
Wi-Fi transceiver
Control module
(Raspberry Pi)
Battery
Black semi-cylinder
Color tracking
marker
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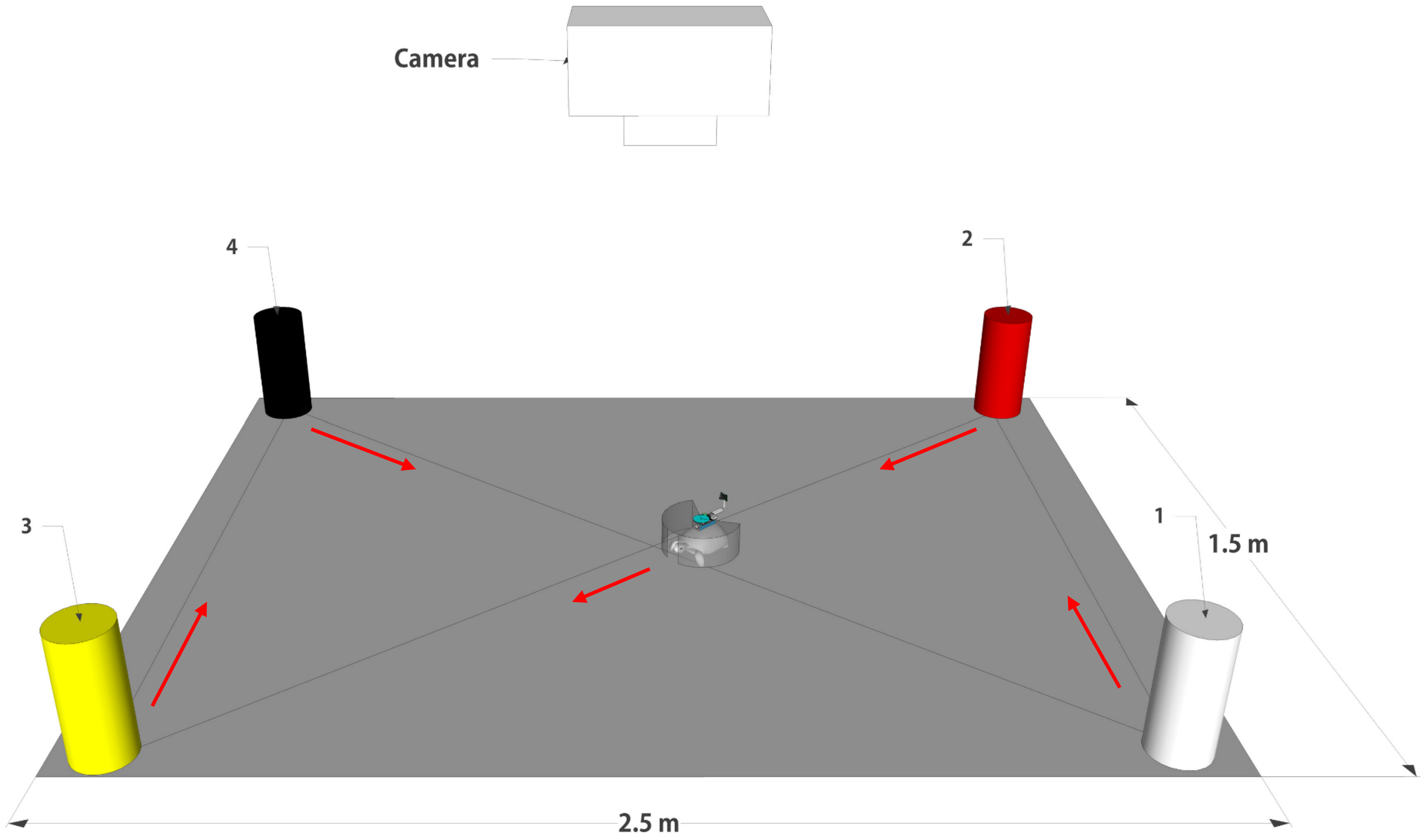
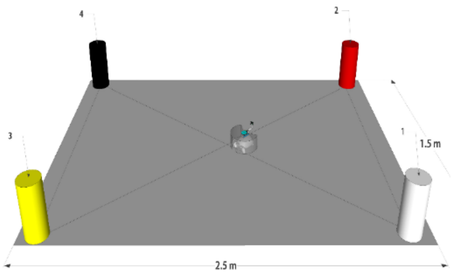
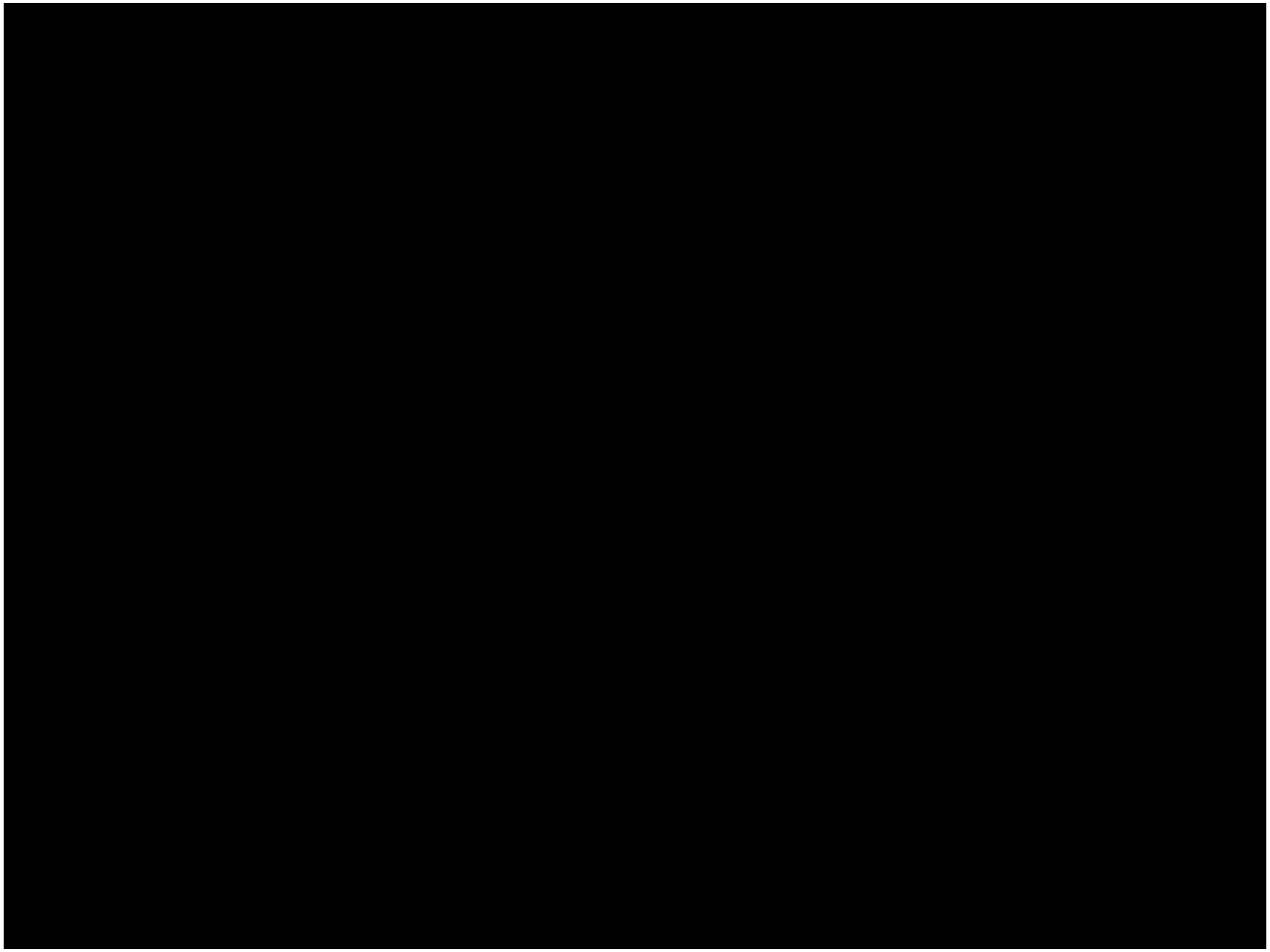
Indoor test

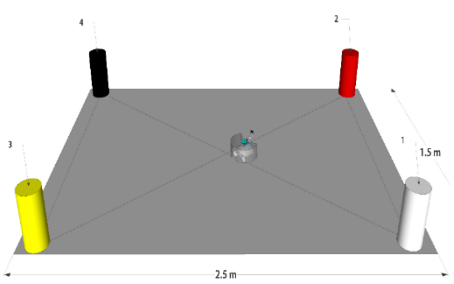


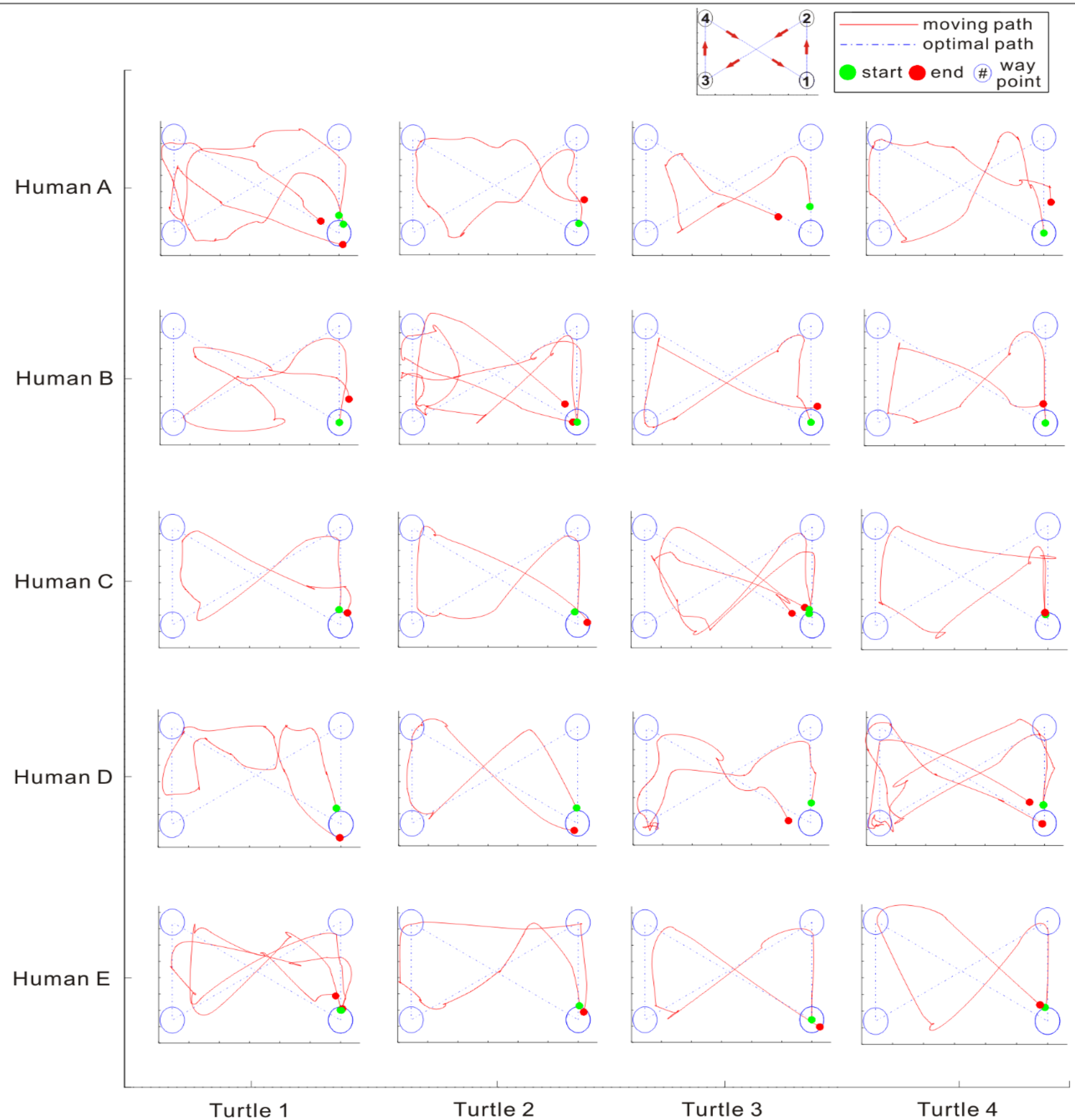
Indoor test



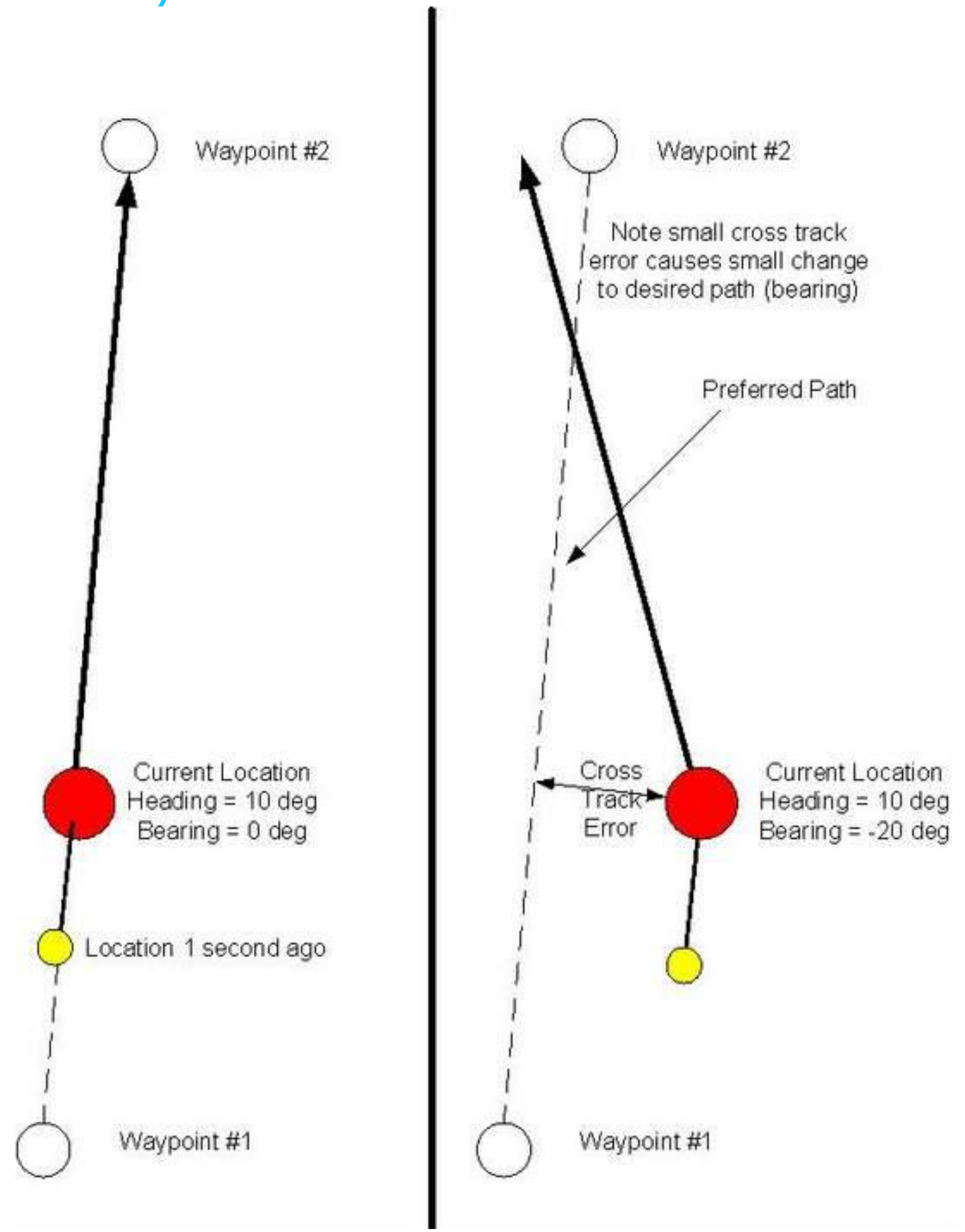


Indoor test

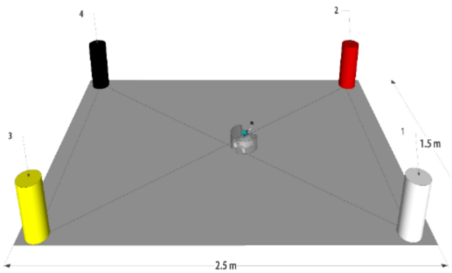

4
2
3
1
1.5 m
2.5 m


4
2
3
1
moving path
optimal path
start
end
#
way point
Human A
Human B
Human C
Human D
Human E
Turtle 1
Turtle 2
Turtle 3
Turtle 4

CTE (Cross Track Error)



Indoor test

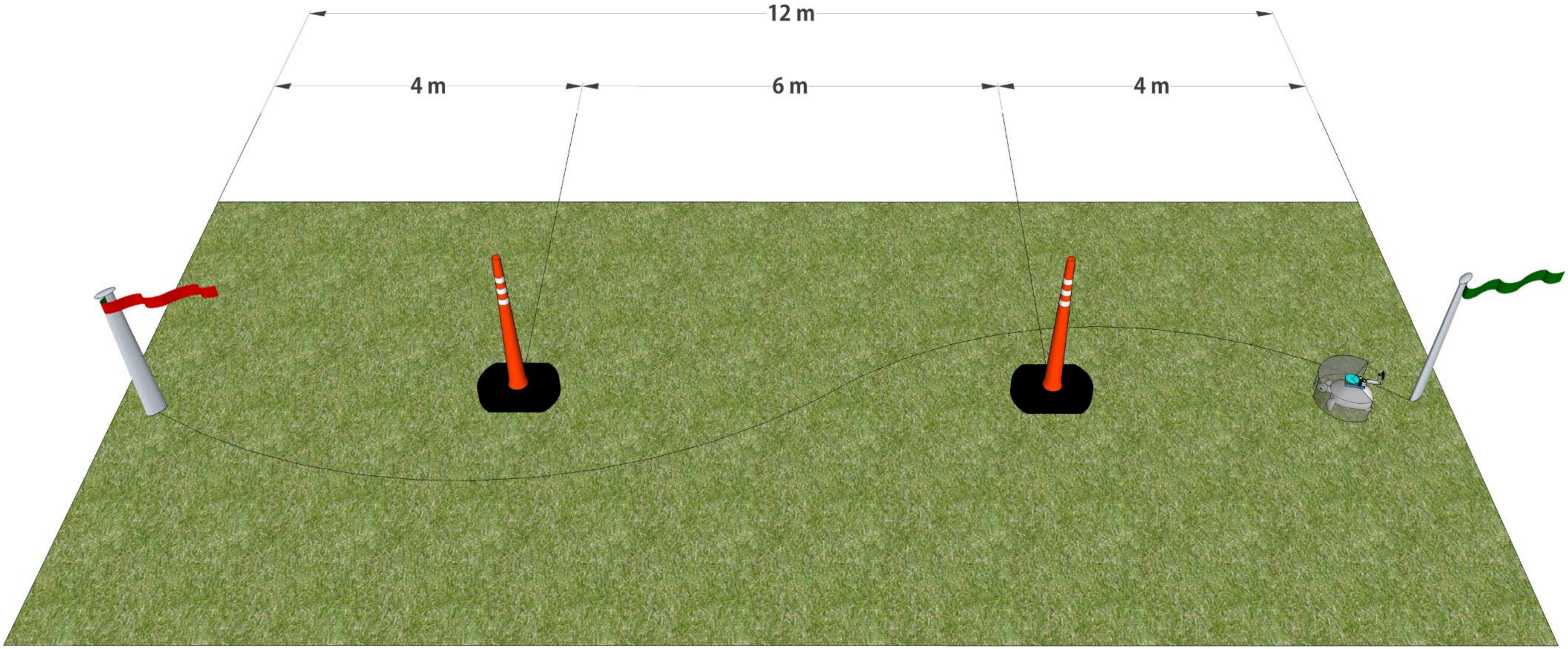


Subject (Human)	A	B	C	D	E	Total
Avg. travel time (s) (± Std)	497.2 (± 189.2)	758.6 (± 141.3)	531.6 (± 69.2)	425.2 (± 64.5)	479.4 (± 83.3)	**538.4 (± 166.2)**
Avg. travel distance (cm) (± Std)	911.1 (± 3.0)	911.5 (± 14.5)	908.4 (± 10.4)	901.5 (± 10.4)	905.3 (± 9.6)	**907.5 (± 10.9)**
Avg. speed (cm s-1) (± Std)	2.07 (± 0.63)	1.27 (± 0.34)	1.74 (± 0.26)	2.17 (± 0.35)	1.95 (± 0.38)	**1.84 (± 0.52)**
Avg. CTE (cm) (± Std)	27.99 (± 3.00)	28.37 (± 14.52)	25.32 (± 10.36)	18.41 (± 10.35)	22.17 (± 9.59)	**24.45 (± 10.92)**

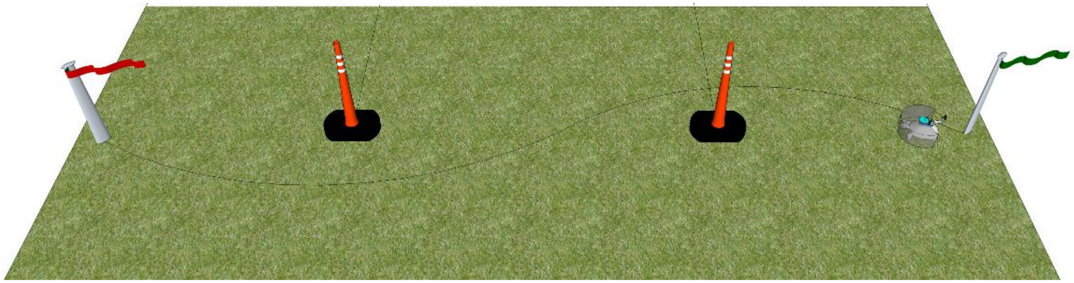
Optimal travel distance = 883.10 cm

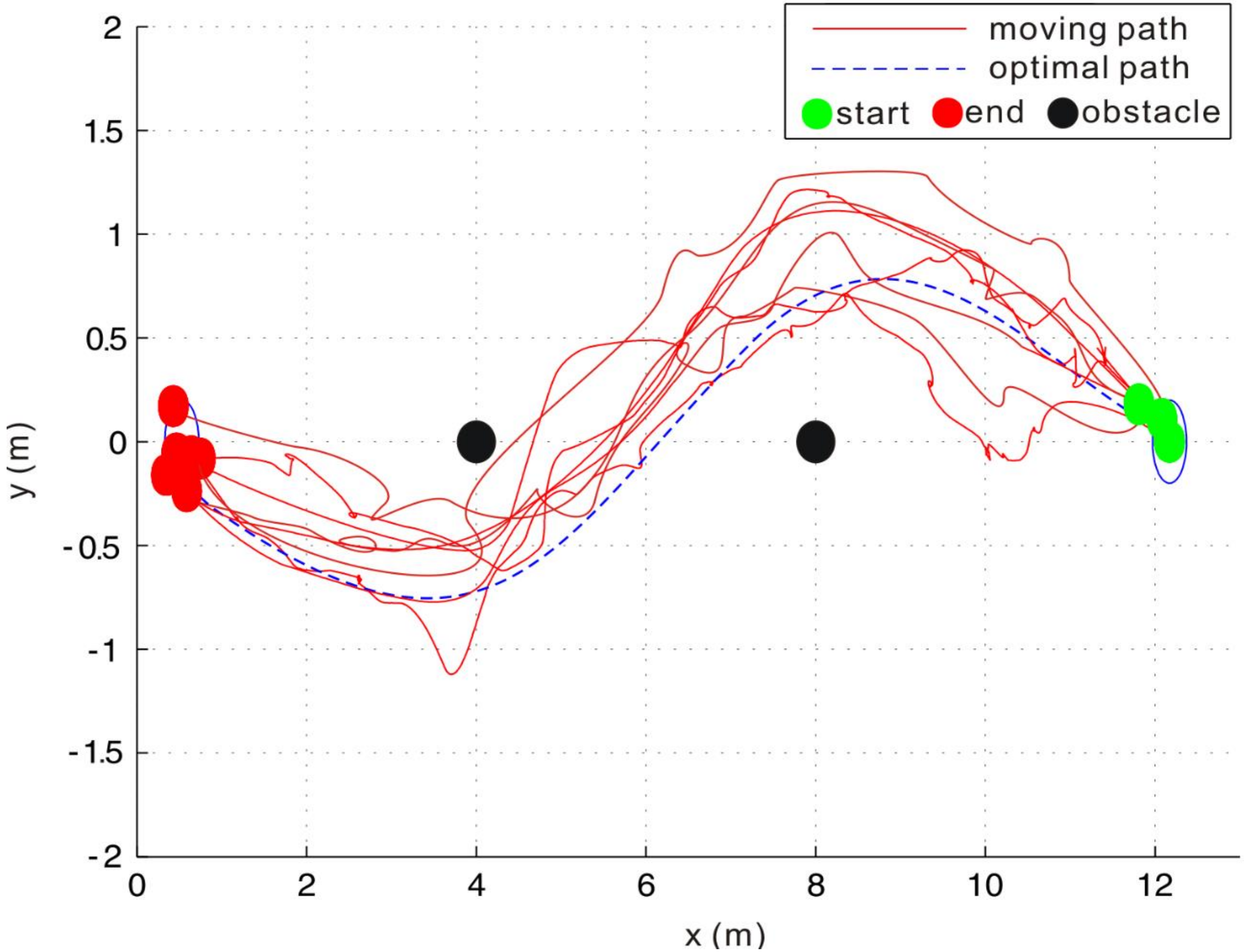
Avg. speed of comparison group (unstimulated turtle) = 2.53 (± 0.42) cm s-1

Outdoor test



Outdoor test





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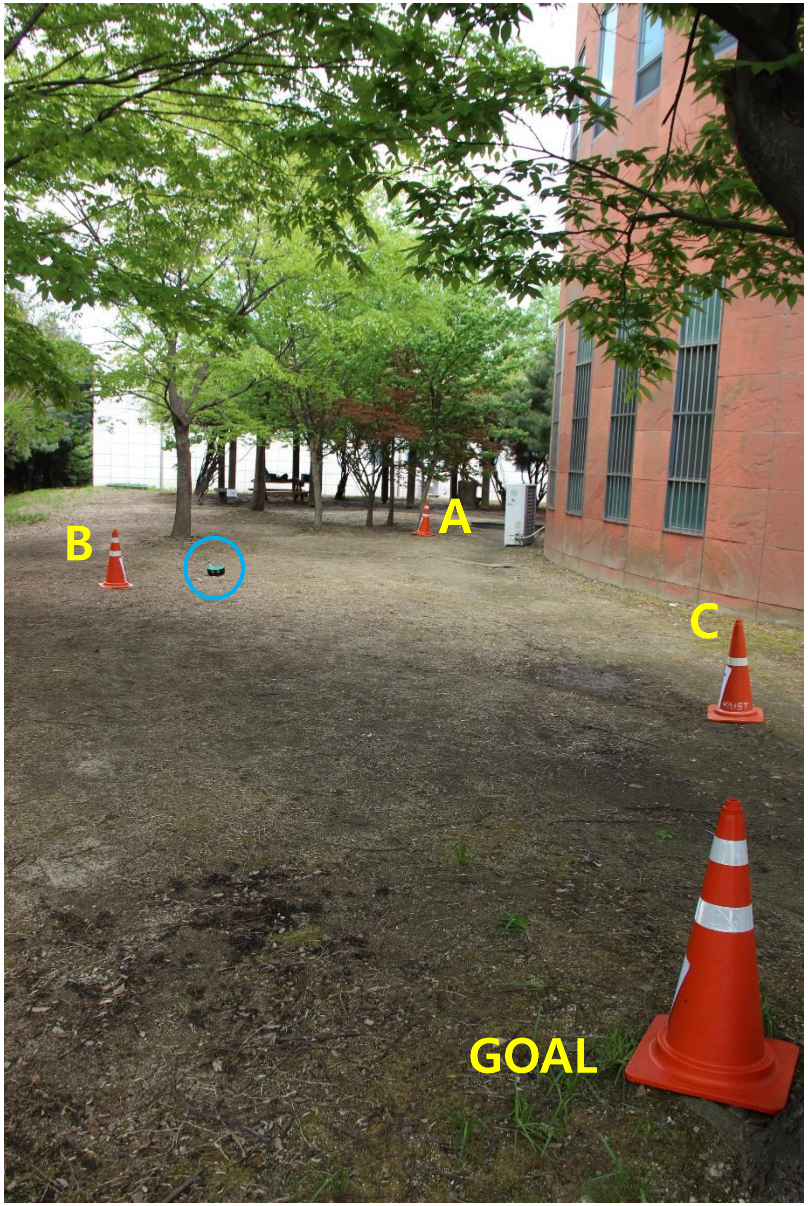
Field test

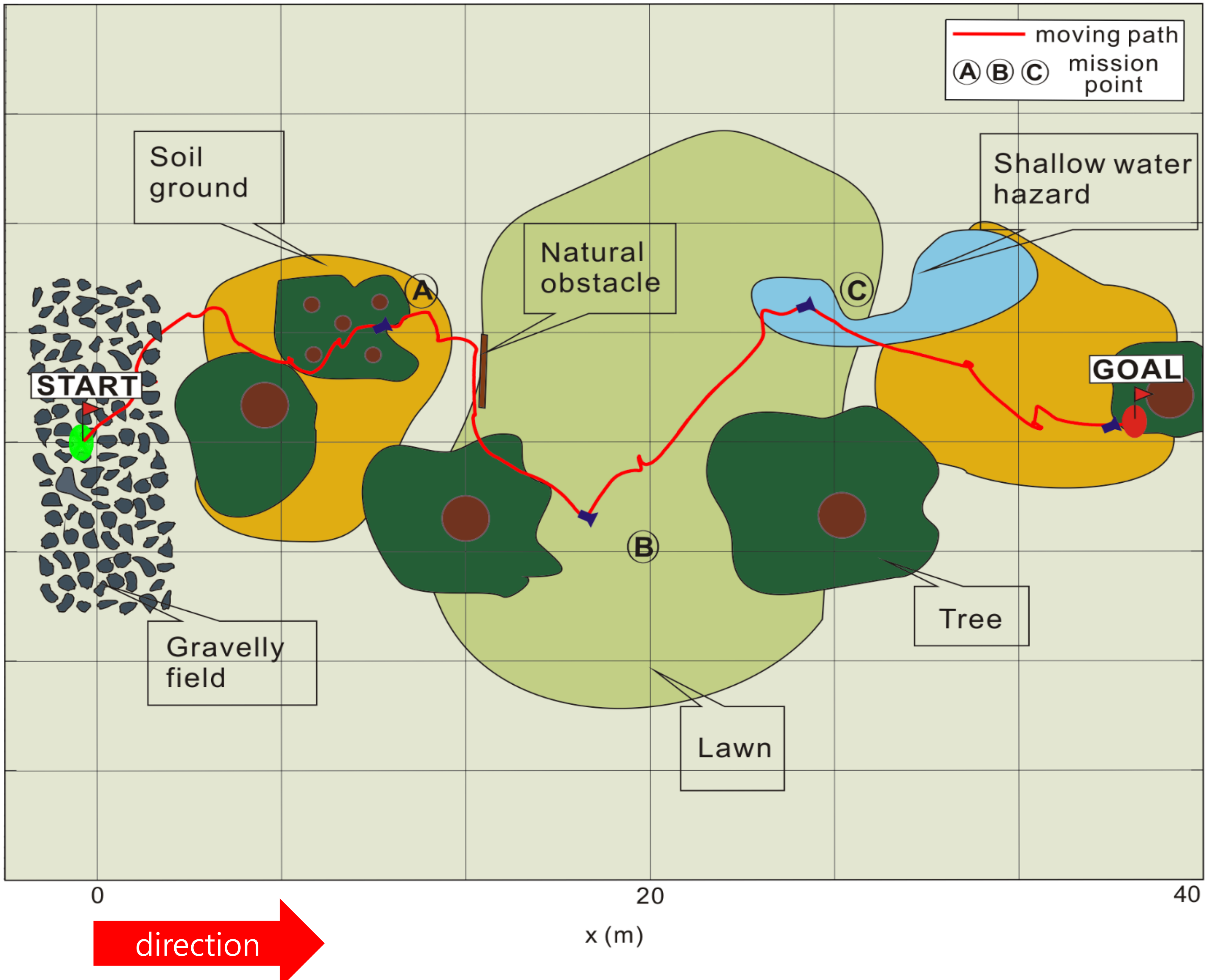


- The turtle covered a **40 m** route that presented **various geomorphological conditions** (gravelly field, soil, lawn-like surfaces, shallow-water hazards, etc.) and natural obstacles.

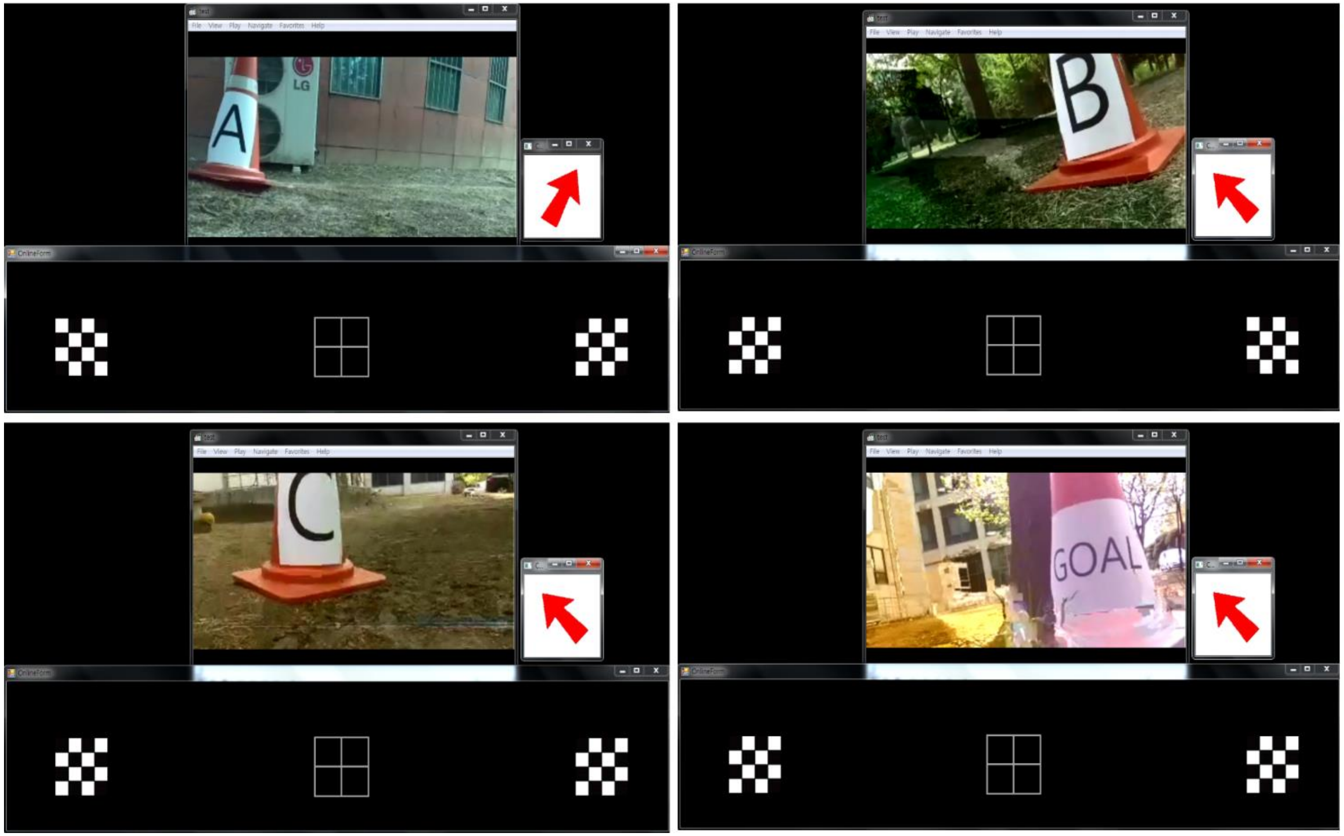
- Mission for cyborg turtle

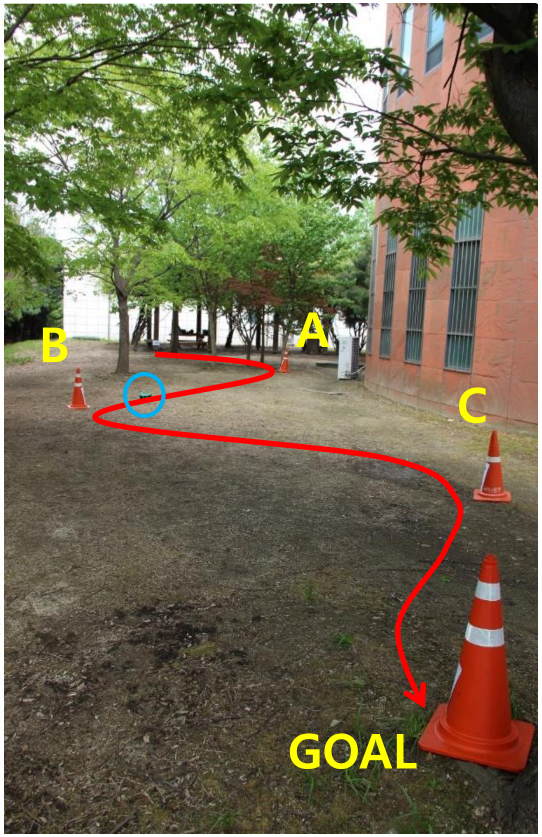
Capture images at each mission point

Field test


moving path
Ⓐ Ⓑ Ⓒ mission point
Soil ground
Natural obstacle
Shallow water hazard
START
GOAL
A
B
C
Gravelly field
Tree
Lawn
0
20
40
x (m)
direction

Field test





Summary

- We examined one of the essential responses for an organism's survival: obstacle avoidance. by providing a visual stimulus that causes the behavior, we remotely guided a turtle's walking behavior.

- We examined the turtle's visual recognition of obstacles under various conditions. We found that the turtles, **recognizing the white object as open space, headed for it regardless of other conditions**.

- We tried to find out the turtle's obstacle recognition distance. We discovered that **no matter what the obstacle's height (apparent size), the turtle did not come closer to it than 15cm**.

- We then designed a simple device and found that the more the turtle's view was blocked by the obstacle, the sharper it turned away from it.

- By applying the above results, **we were able to successfully guide the turtle's walking paths.**

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Summary

- We redesigned the stimulation device and **upgrade hardware** to implement **outdoor experiments**.

- We then performed three kinds of tests. (indoor, outdoor, field test)

- The results of these three tests showed that **our scheme is still valid under indoor condition as well as outdoor condition**.

- **Published on PLoS One journal. (IF. 3.73, April 17, 2013)**

- **Submitted to Journal of Bionic Engineering (Revision)**

Target animal: Carp

Common Carp (*Cyprinus carpio*)

- Superior visual sense
- Spirited movement
- Easy to maintain in the laboratory
- 15 carps (average length = 35 cm) were grown indoors in laboratories

Literature survey & Preliminary experimentation

- Through the literature survey and preliminary test, we could know that **vision is dominant sense** for its locomotion.
- Generally, through the **vision sense**, fish **detect the obstacles** or **check its position**. [5]
- A carp has very large field of view (30 m ahead, 270 degrees in each eye).
- It could classify color in visible rays (400~750nm), it respond to likes green and yellow color/light sensitively.
- It also has a '**epiphysis**' which could **detect sensitively variation in contrast**.
- So, we focused on visual sense and planed the experiments.

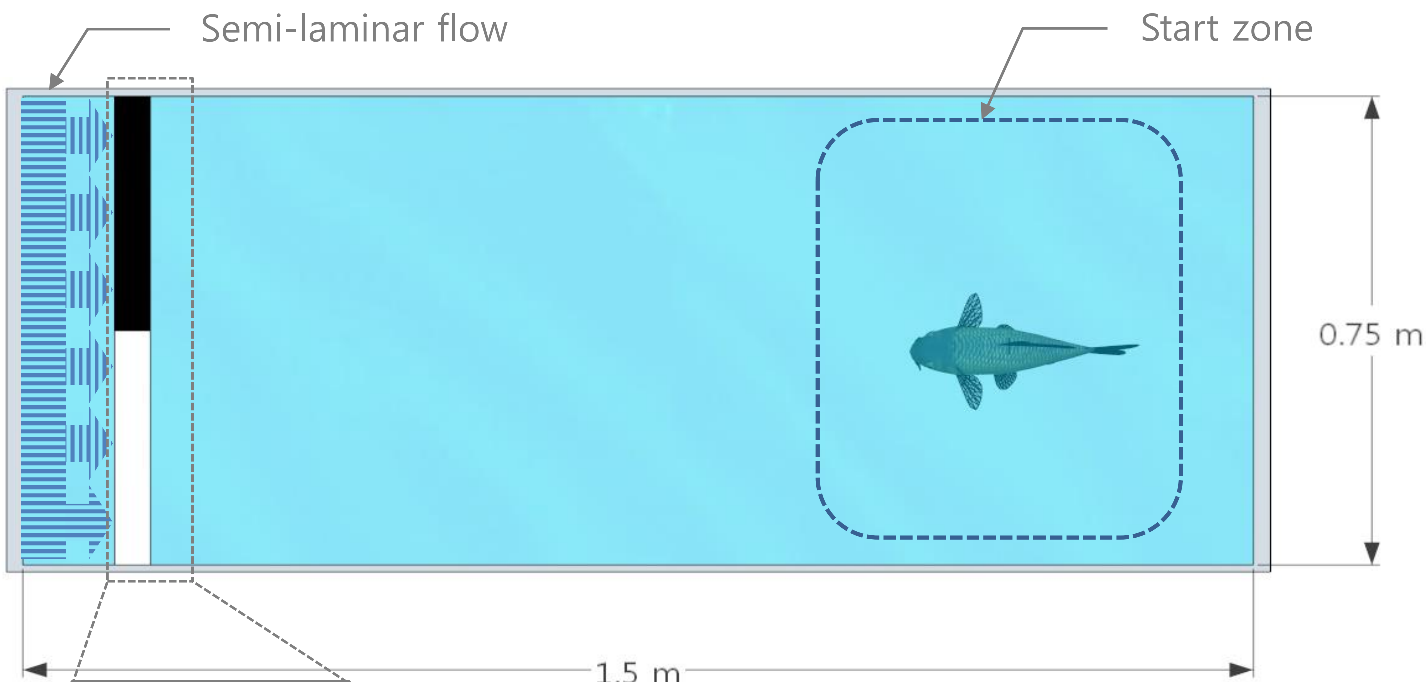
[5] Shaw, E. (1978). Schooling fishes: the school, a truly egalitarian form of organization in which all members of the group are alike in influence, offers substantial benefits to its participants. American Scientist, 166-175.

Literature survey & Preliminary experimentation

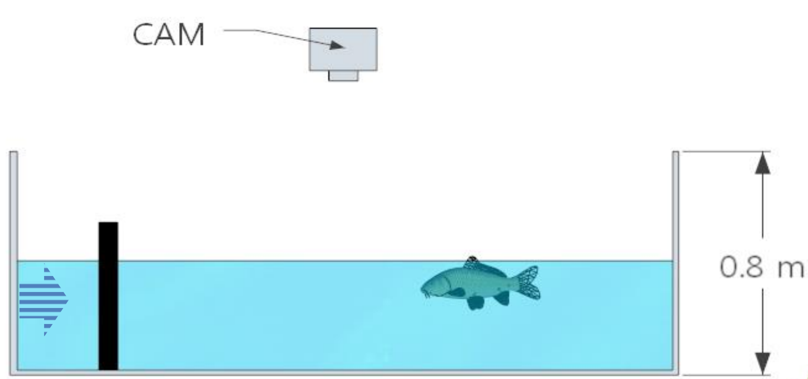
Left Turn
(blocked Right sight)

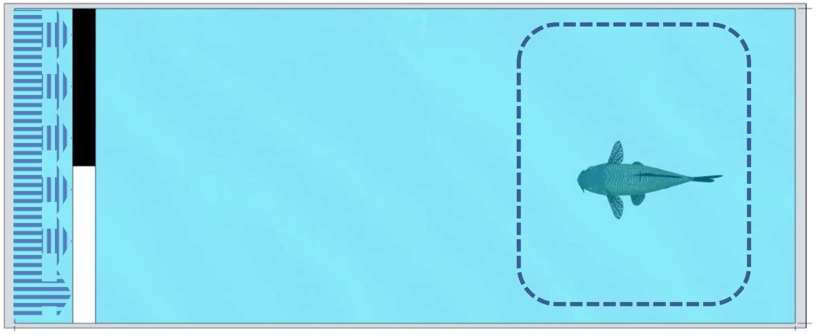
Right Turn
(blocked left sight)

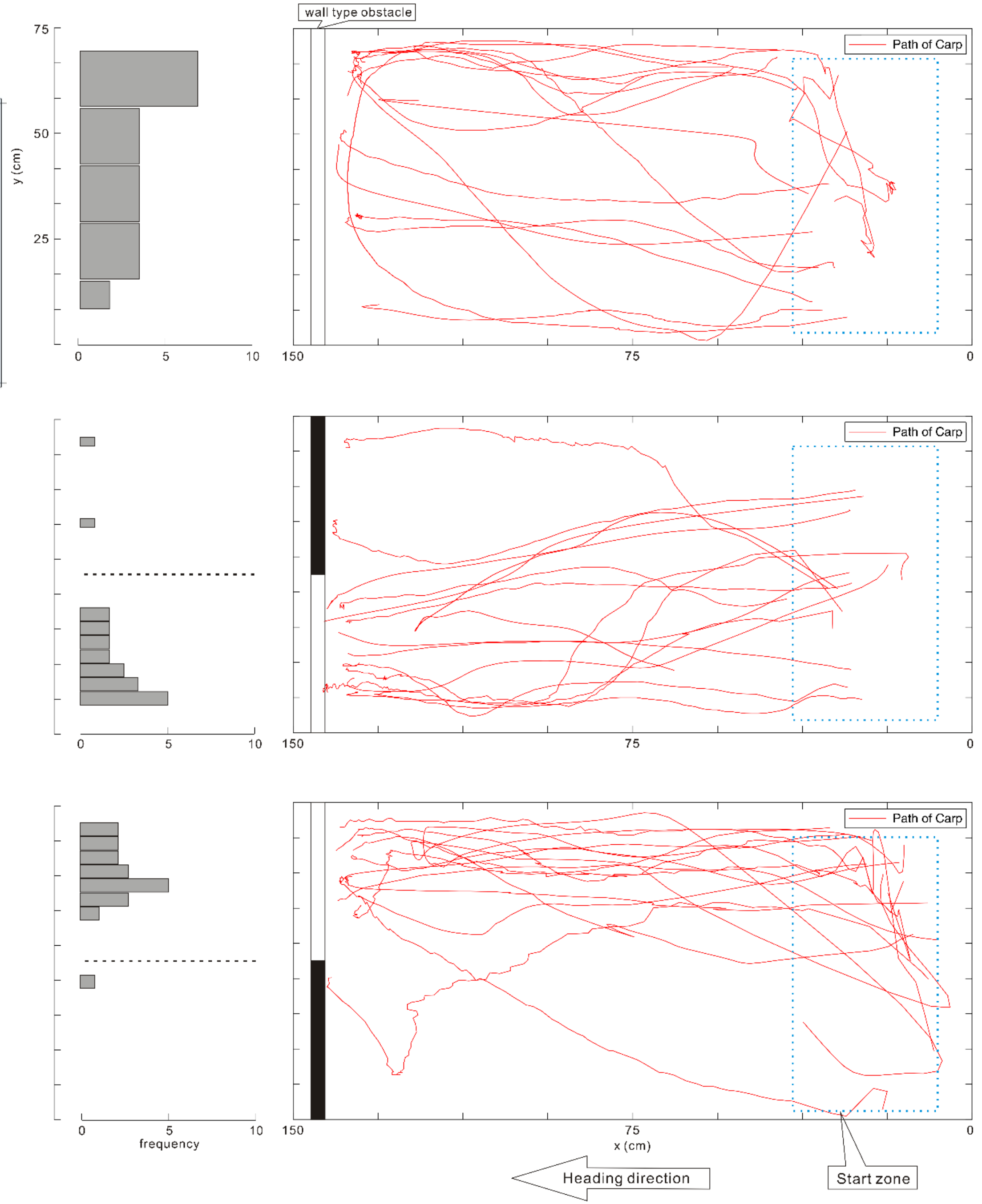
Obstacle avoidance test - Closed loop



<Wall type obstacle>



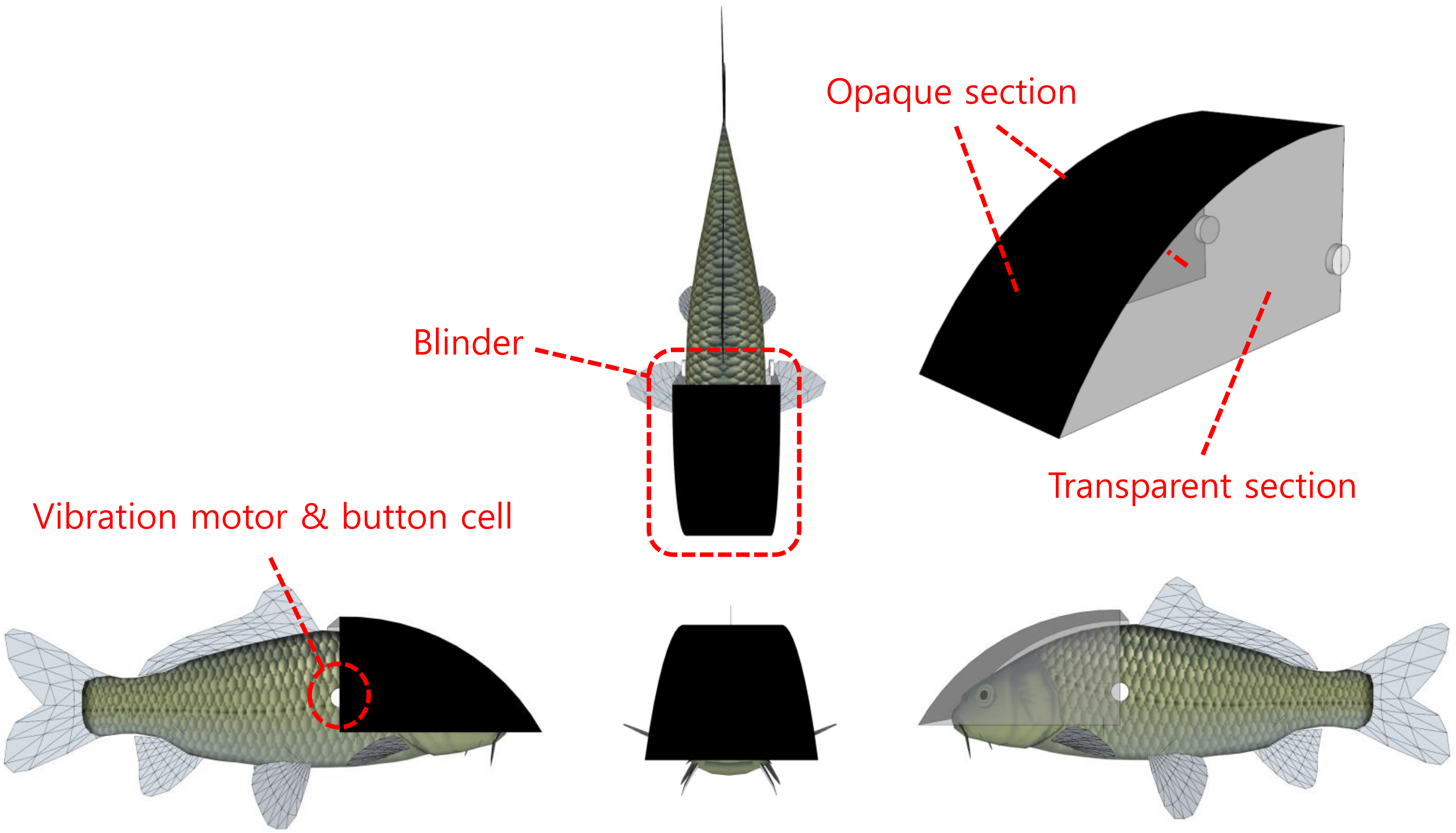




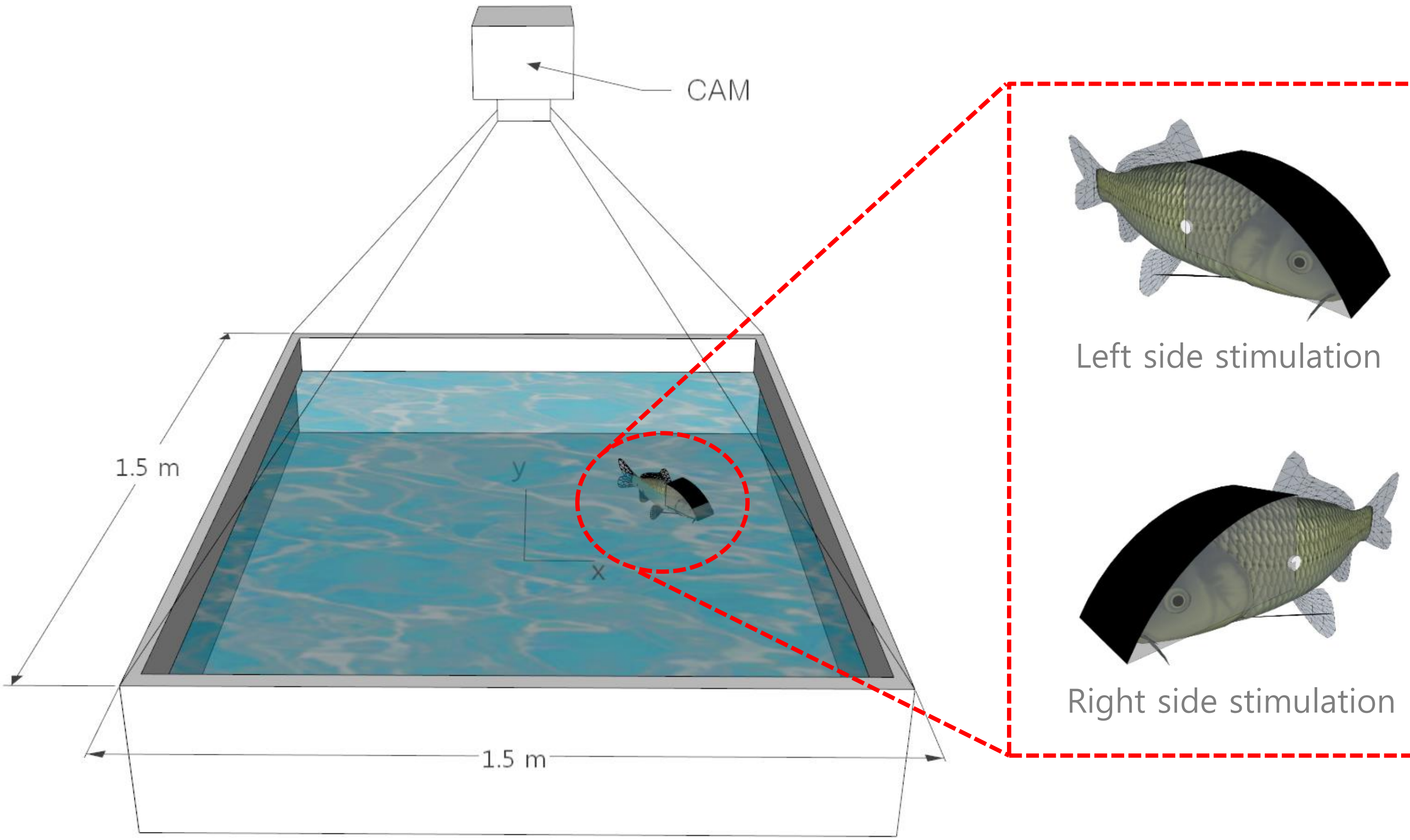
- The carp **faced toward the transparent side**, but avoided the black side.

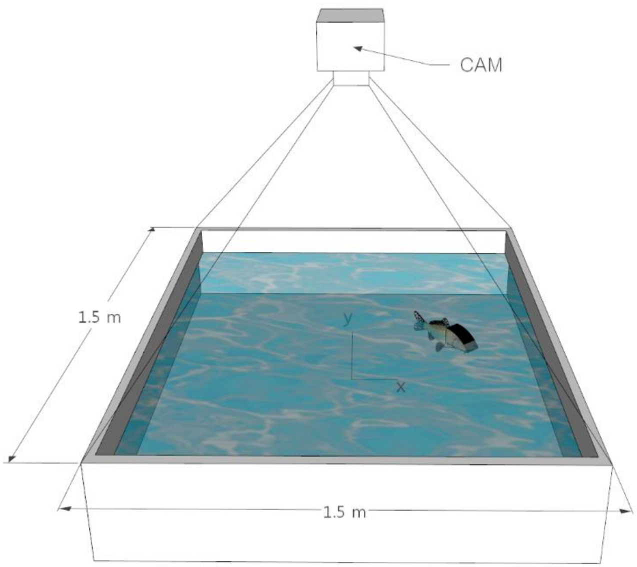
- It recognized the black wall as an obstacle, but not the transparent wall

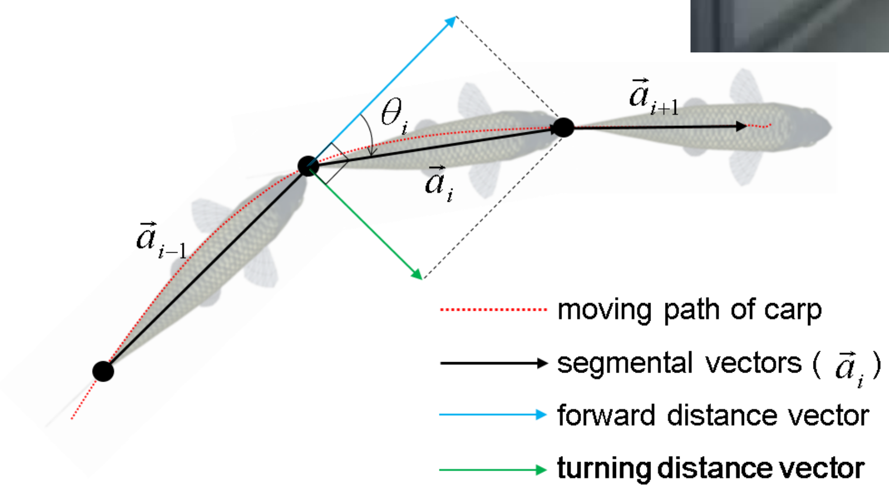
Obstacle avoidance test - Open loop



Obstacle avoidance test - Open loop





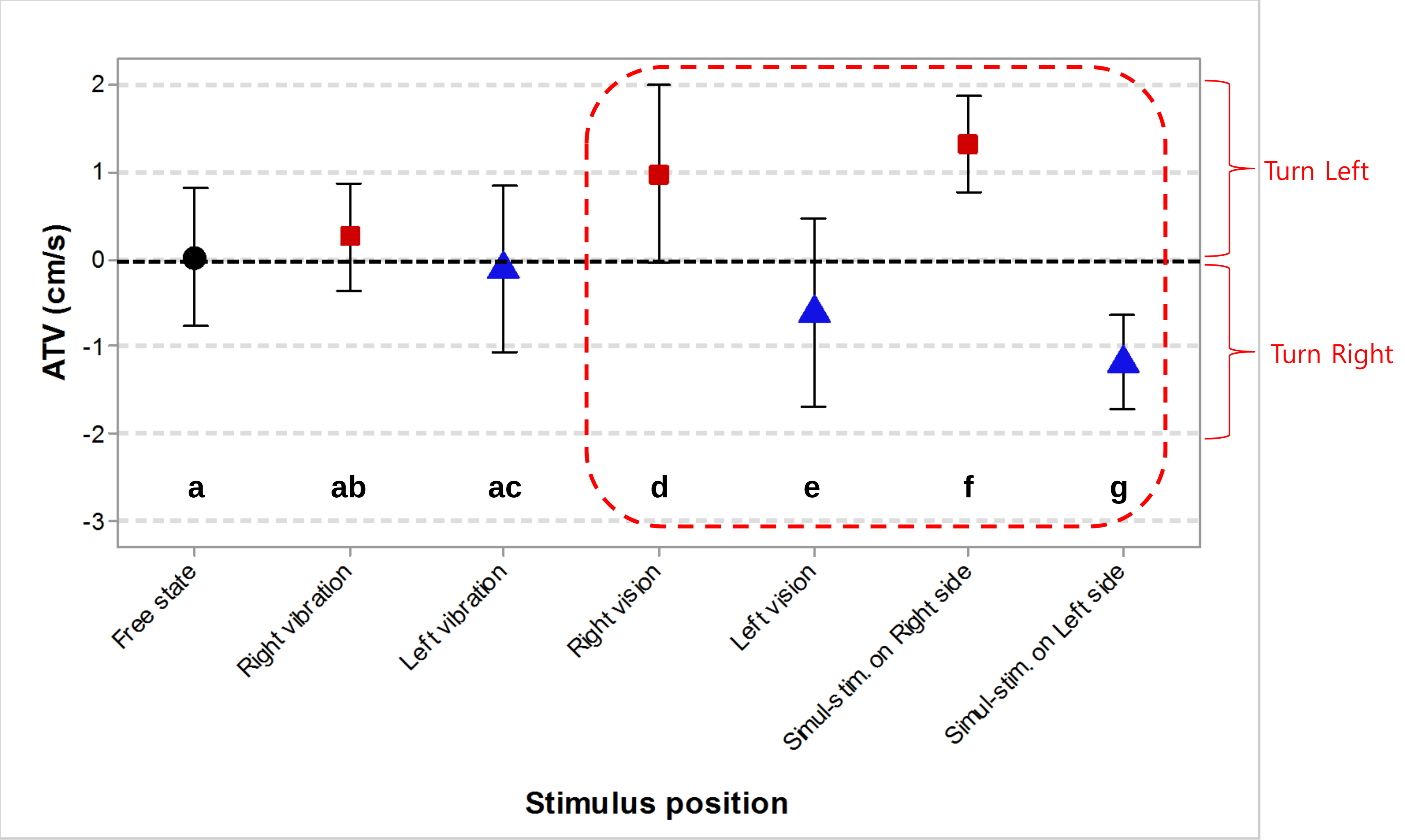


$$\mathrm{ATV} = \frac{\mathrm{TD}}{(\text{total travel time})} \quad \text{with} \quad \mathrm{TD} = \sum_{i=1}^{n} |\vec{a}_i| \sin\theta_i$$

Statistical verification

- Each experiment was conducted **50 times**, and each session was recorded for 300 s, with **15 carp** being used at random.
  - ✓ In turtle case, one of the critical comment is 'Lack of samples' and 'Number of experiments'.

- We analyzed the results of each experiment using ATV and the **M-W U test**.
- In all cases where data were compared multiple times, we used a **Bonferroni correction** for **multiple comparisons of each trial after stimuli presentation**.
- Lower case letters represent statistically homogeneous groups.
  - ✓ For example, groups "a" and "b" are significantly different, whereas "a" is not significantly different to "ab," which shares membership with group "a."



ATV (cm/s)
2
1
0
-1
-2
-3
a
ab
ac
d
e
f
g
Turn Left
Turn Right
Free state
Right vibration
Left vibration
Right vision
Left vision
Simul-stim. on Right side
Simul-stim. on Left side
Stimulus position

Summary

- This study was designed using the simple concept that fish movement patterns may be controlled by stimulating their visual obstacle avoidance instinct.
- Through two basic experiments, we demonstrated that the stimulation of visual senses could be used to guide fish along specified moving paths.
- Especially, we found out **carps show turning behavior more clearly when we give simultaneous stimulation**, vision and vibration.
- Therefore, the turning direction of carp is more effectively controlled when both stimulations are given in combination.
- We believe these findings could be used to study on fish guidance system.
- Also, we should be carefully studied more this topic (e.g. simultaneous stimulation) and analyze the experiment result.

Overall summary

- Through these researches, we examined one of the essential responses for an organism's survival: obstacle avoidance.
- By providing an external stimulus that causes the behavior, we remotely guided our target animal's moving path.
- We first examined the turtle' s visual obstacle avoidance behavior. By applying the experiment results, **we were able to successfully guide the turtle' s walking paths**.
- Further, **we attained success in remotely guiding the path of turtle in outdoor condition**.
- Lastly, we expanded our target animal area, choose carp and implement primary experiments for developing a remote guidance system.

Contributions

- This research demonstrate the feasibility of animal (especially in turtle & carp) guidance system by evoking its innate instinctive behavior.

- We find out specific behavior patterns for our target animals.
  - Turtle
    - ✓ They recognizing the **black object as an obstacle**, rather than the white one. (they recognizing **white object as open space**, headed for it regardless of other conditions.)
    - ✓ They **do not come closer to it than 15cm** without regard to the obstacle's height.
  - Carp
    - ✓ They avoid **visual obstacle stimulation effectively** .
    - ✓ They determine turning direction effectively through the simultaneous stimulation.

Contributions

- If our scheme is so for animal remote guidance system, we could resolve some of problems that invasive system have. (life-threatening (surgery), maintenance and sustainability etc.)

- Additionally,
  - ✓ This is the first attempt to guide reptile case.
  - ✓ Also, we implemented guiding test in outdoor condition.
  - ✓ There was few researches on of animal guidance system by evoking innate behavior when we prepare our first paper (in 2012).

Ongoing & Future works - with our research team

- Research on the remote guidance system by ‘experience based behavior’.
- Automatic guidance system using line-of-sight guidance algorithm.
- Collaboration with photic stimulation research.
- Further studies & data analysis on carp case including stimuli manner.

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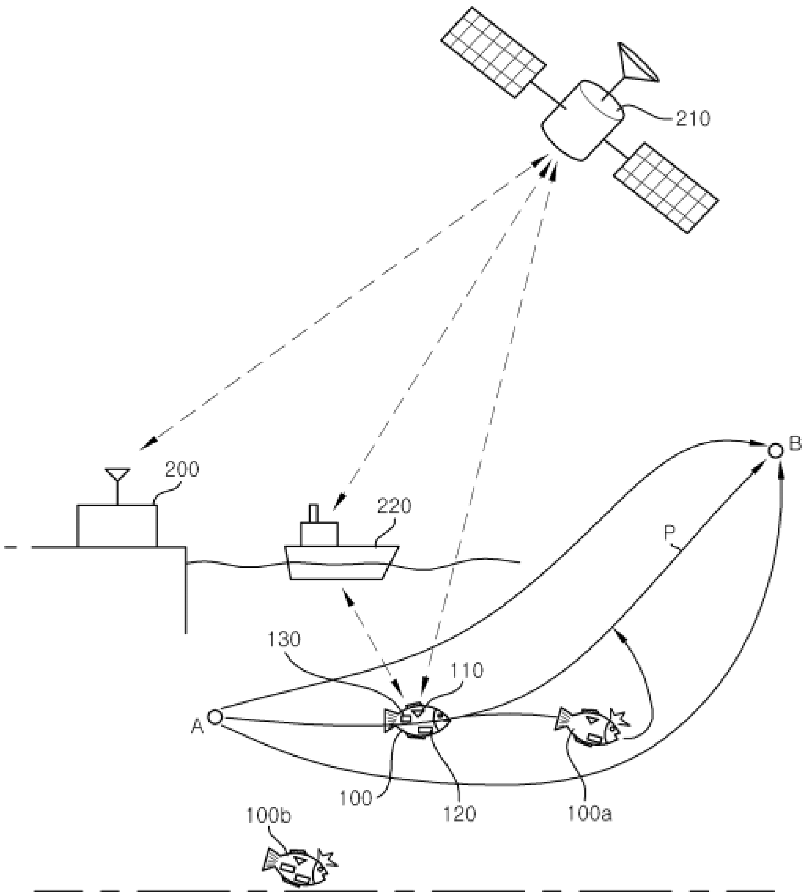
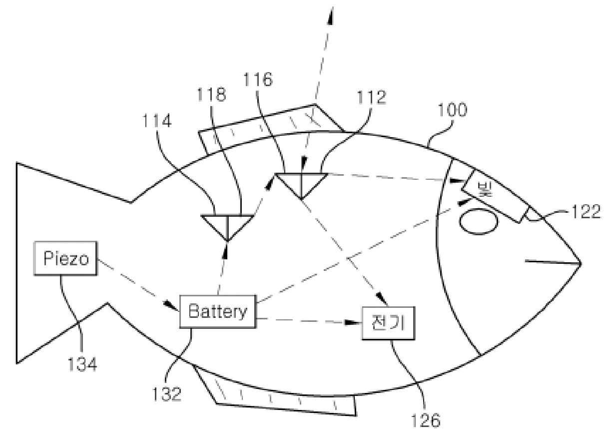
Q & A

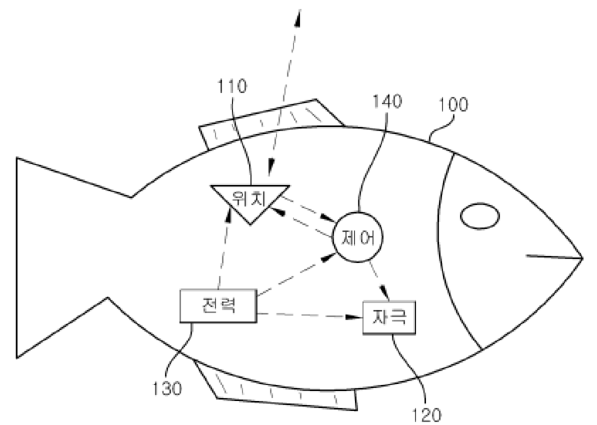
Thank You

Patent





도면3



- MEHTOD AND APPARATUS FOR MOVEMENT CONTROL OF A LIVING THING (Applied in 2010, Final registered in 2012)

조성호 교수님

- 여러 가지 연구를 하나의 주제로 연결하는 것이 필요해 보임.
  - ✓ 내용 전반에 걸쳐 주제의 통일성을 유지하는 방향으로 수정하였고, 더불어 연구의 제목 또한 좀 더 specific 하게 수정함.

- 연구내용 정리를 위해 좀 더 공학적 논리검증을 활용하면 좋겠음.
  - ✓ 기존 발표에서 삭제했던 공학적 논리검증을 통한 접근절차를 추가하였고, 다양한 공학 논문 및 저서를 통한 문헌조사 및 공학기초실험을 토대로 최종실험을 설계한 내용을 추가하였음. (특히, 중요정보의 경우 페이지에 참고문헌 직접표기)

- 결과를 일반화하는 표현들을 조심할 필요가 있음
  - ✓ 자료 전반 걸쳐 일반화하는 표현들을 수정하고, 특히 연구결과를 논의 하는 부분에 있어서 우리가 얻은 결과의 대해서만 명확히 제시함.

정현 교수님

- BCI 부분은 연구 전체의 초점을 흐리는 경향이 있음
  - ✓ BCI 연구부분은 발표자료의 중심에서 삭제하고, 추가자료를 통해 본 시스템의 활용측면에서 시도된 연구로서만 제시함.

- Input 자극에 따른 생물체의 부정확한 output variation을 지속적으로 update하여 조종의 정밀도를 향상시키는 방향이 필요할 듯.
  - ✓ 현재 연구 및 앞으로의 연구진행에도 매우 도움이 되는 조언이라 생각함. 본 조언을 연구의 개선점 및 future work 부분에 반영하고, 또한 해당 부분에 대한 논의를 학위논문에 따로 기술하겠음.

- 실험 및 내용 진행에 있어, 논리적 구성과 통계적 완결성을 좀 더 확보할 필요가 있다.
  - ✓ 논리적 구성을 확보하기 위해 전체내용을 수정하였으며, 실험의 통계적 완결성을 확보하기 위해 생물과 김대수 교수님의 자문으로 실험 및 분석절차를 설계하였음.

김진환 교수님

- 생물체 조종 시스템에 대한 장점(유용성)이 크게 과장되어 있음. 공감이 되지 않음
  - ✓ 맞음. 본 시스템은 장점과 단점을 모두 가지고 있음. 장점 만이 부각된 부분이 있었던 것이 사실이고, 현재는 장단점 두 가지 부분을 pair하게 말씀 드리려고 노력하였고, 도입 및 마무리에서 연구의 의의 측면의 논의를 중점으로 기술함.

- 생물체 특성에 대한 좀 더 전문적인 연구가 필요해 보임.
  - ✓ 절대적으로 공감함. 그래서 거북 실내조종 이후에는 생물체 실험 전반에 대해 생물학과 김대수 교수님의 자문을 받아 진행함. 그렇지만 아직까진 특정 생물체 (예. 잉어) 특성 분석에 대한 전문성이 부족한 것은 사실. 해당 부분을 보완하기 위하여 좀 더 철저한 접근을 통해 연구를 진행하겠음.

- 실제적 유용성 보다는 feasibility demonstration에 초점을 맞추는 것이 현실적인 scope 일 듯
  - ✓ 아직 실제적 유용성을 논하기에는 시스템이 많이 부족한 것이 현실임. 매우 적합한 지적이라 생각하고, 본 발표자료 에서는 feasibility demonstration에 초점을 맞추는 방향으로 전체적인 논점을 수정함.

김진환 교수님

- 박사연구에 합당한 analystical / theorical 한 연구와 기여의 부분을 어떤 곳에 둘 지 생각해 보았으면 함
  - ✓ 연구의 가장 기여를 말한다면, creative한 연구를 했다는 점에서 의의를 두고자함.
  - ✓ Practical 과 theorical 로 나누어 생각한다면, 아래와 같이 말씀드리고 싶음.
  - ✓ 본 연구의 기여부분을 크게 두 가지 부분으로 생각함
    - ➢ 행동생물학 실험을 통하여 타겟 생물체(거북, 잉어)의 특정한 행동패턴을 파악하고 자극에 대한 특정한 행동패턴을 알아냄.
    - ➢ 이러한 생물체의 자발적인 습성을 이용한 생물체 guiding 시스템 제안

  - ✓ 행동생물학적 측면 (theorical)
    - ➢ 먼저, 생물체에 본능에 대한 문헌연구를 통해 기초지식 확립
    - ➢ 장애물 회피본능 자극에 대한 다양한 실험
      - ❖ 자극 원 변화실험 / 인식 실험
      - ❖ Open loop 자극부여

        - 거북에게 open loop 자극을 줄 수 있는 자극장치 설계 후 실험

        - 이전에는 거북은 비롯한 타 생물체에서도 이런 방식의 자극실험은 거의 존재하지 않았음
      - ❖ 이에 따른 행동패턴 분석 후, 특정 패턴 발견.

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김진환 교수님

- 박사연구에 합당한 analystical / theorical 한 연구와 기여의 부분을 어떤 곳에 둘 지 생각해 보았으면 함
  - ✓ 공학적 측면 (practical)
    - ➢ 기존의 생물체 조종시스템의 단점들을 일부 해결할 수 있는 방법/시스템 제시하고 그 가능성을 보임.
    - ➢ 기존의 주류는 이뤘던 침습적 시스템에서 벗어나, 비침습/자발적 행동을 유도하는 새로운 방법을 제시
  - ✓ 관련 연구 저널 및 연구자
    - ➢ Plos one 개제
    - ➢ M. Maharbiz (사이보그 비틀 연구) 교수 초청 시 우리연구에 대해 관심표명
    - ➢ 첫 번째 연구내용을 발판으로 이어 연구한 다른 주제들도 현재 리비전 또는 제출 중
      - ❖ 대견 학습 논문
      - ❖ 두 번째 거북 논문
      - ❖ 잉어 행동패턴 분석 논문
        - 아직 보완할 부분이 많음. 지속적으로 작업 중
    - ➢ 생물체 조종 또는 Bionic 분야에서는 참신한 연구로 인정받는다는 증거

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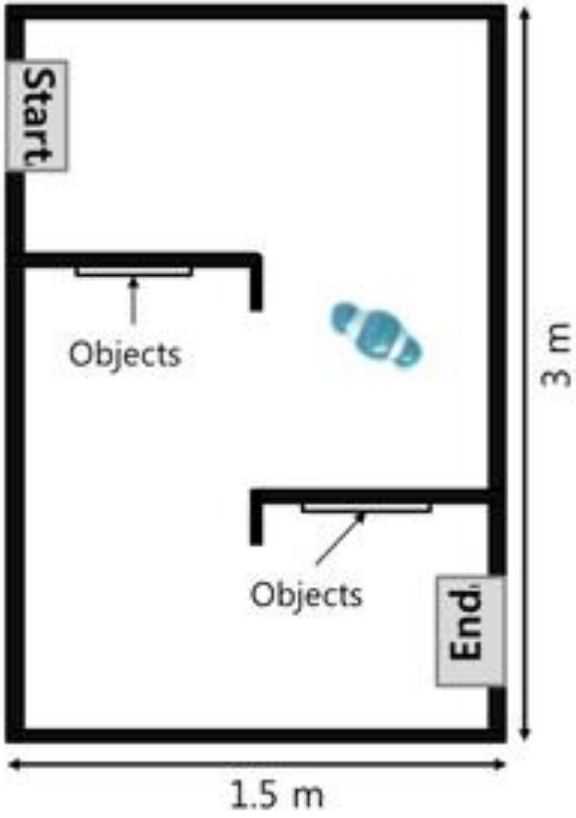
Computational Mechanics
Structural Systems

김진환

- 본능 VS 훈련, 서로 controversal 한 측면이 있음. 둘 다가 장점/단점이 될 수 없음
  - ✓ 훈련에 의한 연구는 현재 연구팀의 김대건 학생의 연구테마로 진행 중.
  - ✓ 현재 실험 및 정리를 마치고 논문 제출 상태.(Bionic Eng.)

Turtle – indoor test - measure



Turtle – indoor test - measure

Subject	Session	Total time (sec)	Distance travelled (cm)	Forward steps (times)	Turning steps (times)	Explored angle (rad)	Transitions (times)	Collisions (times)
A	BCI	507.8	434.4	134.0	44.7	7.0	26.0	0.3
	Manual	483.4	468.0	152.3	45.3	6.8	17.3	0.3
	BCI/Manual	1.05	0.93	0.88	0.97	1.02	1.50	1.00
B	BCI	542.9	432.5	141.7	42.0	7.1	19.7	0.3
	Manual	416.9	440.7	137.3	41.3	6.6	16.3	0.7
	BCI/Manual	1.30	0.98	1.03	1.02	1.09	1.20	0.50
C	BCI	582.8	461.0	150.0	46.7	8.2	19.7	0.3
	Manual	477.9	485.9	143.0	48.3	7.3	19.3	0.3
	BCI/Manual	1.22	0.95	1.05	0.96	1.12	1.02	1.00
D	BCI	609.6	462.8	145.3	41.3	9.1	29.0	0.3
	Manual	460.9	467.7	149.3	41.3	7.3	20.7	0.7
	BCI/Manual	1.32	0.99	0.97	1.00	1.25	1.40	0.50
E	BCI	570.2	427.4	136.3	36.7	7.9	18.7	0.3
	Manual	478.4	410.1	131.7	39.3	6.7	18.0	0.3
	BCI/Manual	1.19	1.04	1.04	0.93	1.19	1.04	1.00
Overall	BCI (±SD)	562.7 (±59.0)	443.6 (±20.6)	141.5 (±7.2)	42.3 (±4.5)	7.9 (±1.0)	22.6 (±5.1)	0.3 (±0.5)
	Manual (±SD)	463.5 (±43.6)	454.5 (±32.7)	142.7 (±10.4)	43.3 (±5.0)	6.9 (±0.7)	18.3 (±3.2)	0.5 (±0.5)
	BCI/Manual (±SD)	1.22 (±0.11)	0.98 (±0.04)	0.99 (±0.07)	0.98 (±0.03)	1.13 (±0.09)	1.23 (±0.22)	0.80 (±0.27)

doi:10.1371/journal.pone.0074583.t002

Carp - Turning behavior test - measure

Types of stimulation	None (Free state)	Vibration		Vision		Simultaneity	
		Right	Left	Right	Left	Right	Left
ATV (cm/s)	+0.0194	+0.2573	-0.1103	+0.9788	-0.6244	**+1.3208**	**-1.1832**
P value	·	0.9533	0.8605	0.4219	0.4340	0.0029	0.0318
"+" and "-" signs indicate left and right turning directions, respectively. The Mann-Whitney U test (M-W U test) with $p < 0.05$ was been used.							

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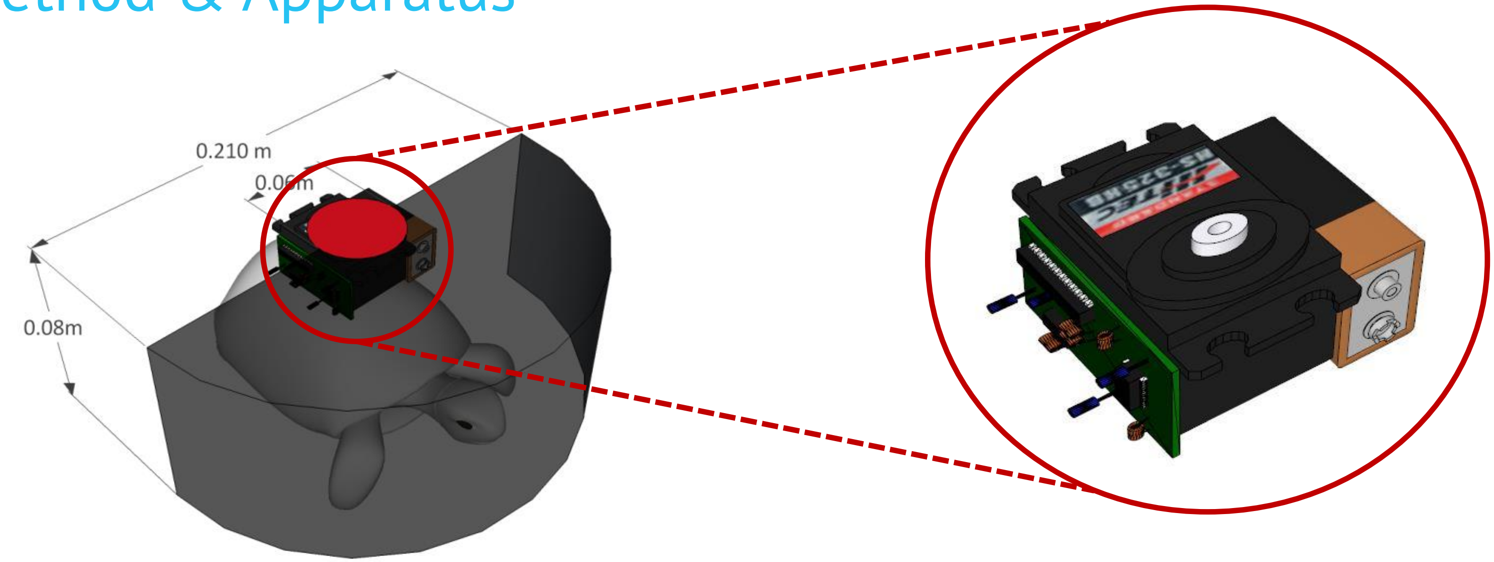
Method & Apparatus



- An embedded control module (5.3x7.5x4.8cm, 133.5g) was mounted on the turtle' s upper shell with the circular color patch for tracking, and a black semi-cylinder was used to block the turtle's view

- The center of a circular color patch (radius=3cm) attached to the center of the turtle' s upper shellwas tracked by a color-based tracker that used a MATLAB (The Mathworks Inc., USA) image processing program developed by Maptic (See http://www.matpic.com).

- A micro controller unit (ARM Cortex-M3, STM32F101V8T6) received an angular value to control the servo motor (Maximum output angle: 2,160 degrees, Resolution: 4.9 degrees, Motorbank, KOREA), which could rotate the black semi-cylinder within ±180 degrees with respect to its body axis, from a PC control software written in C# via Bluetooth communication (Baud rate: 19,200bps, Firmtech, KOREA).

- color-based tracker that used a MATLAB (The Mathworks Inc., USA) image processing program developed by Matpic (See http://www.matpic.com). The average distance between the center of the patch and the end of the turtle's head was 6cm.

- The raw data from the color-based tracker was post-processed by projective transformation mapping of the oblique view to the top view,

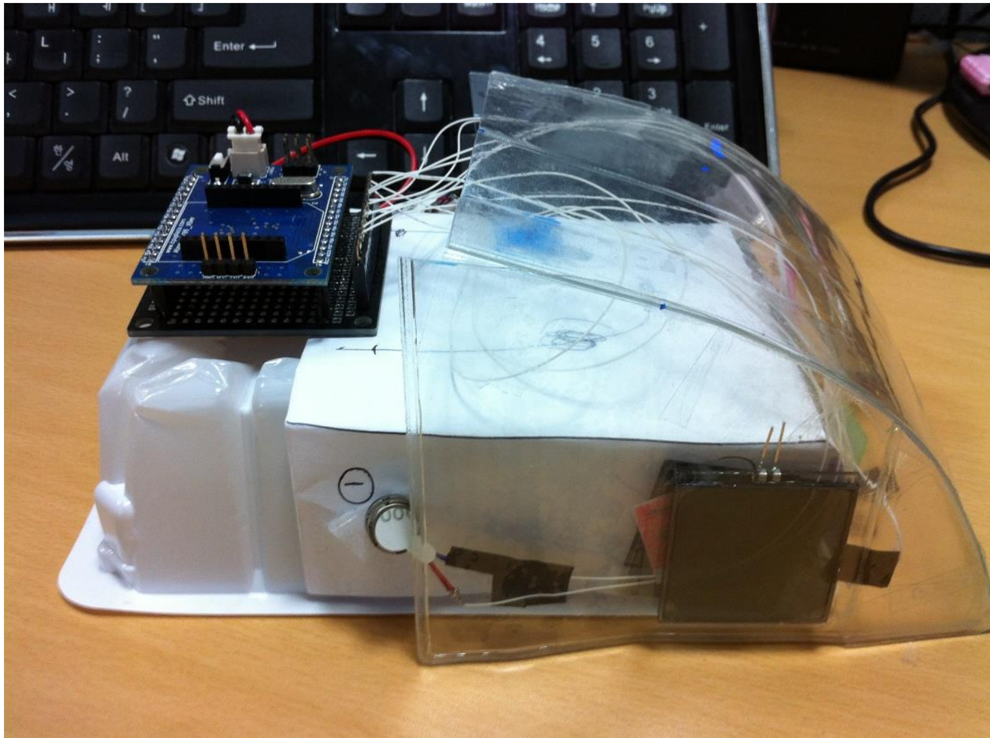
- a Kalman filter with linear models was used for both the dynamics of the system and the observation process.

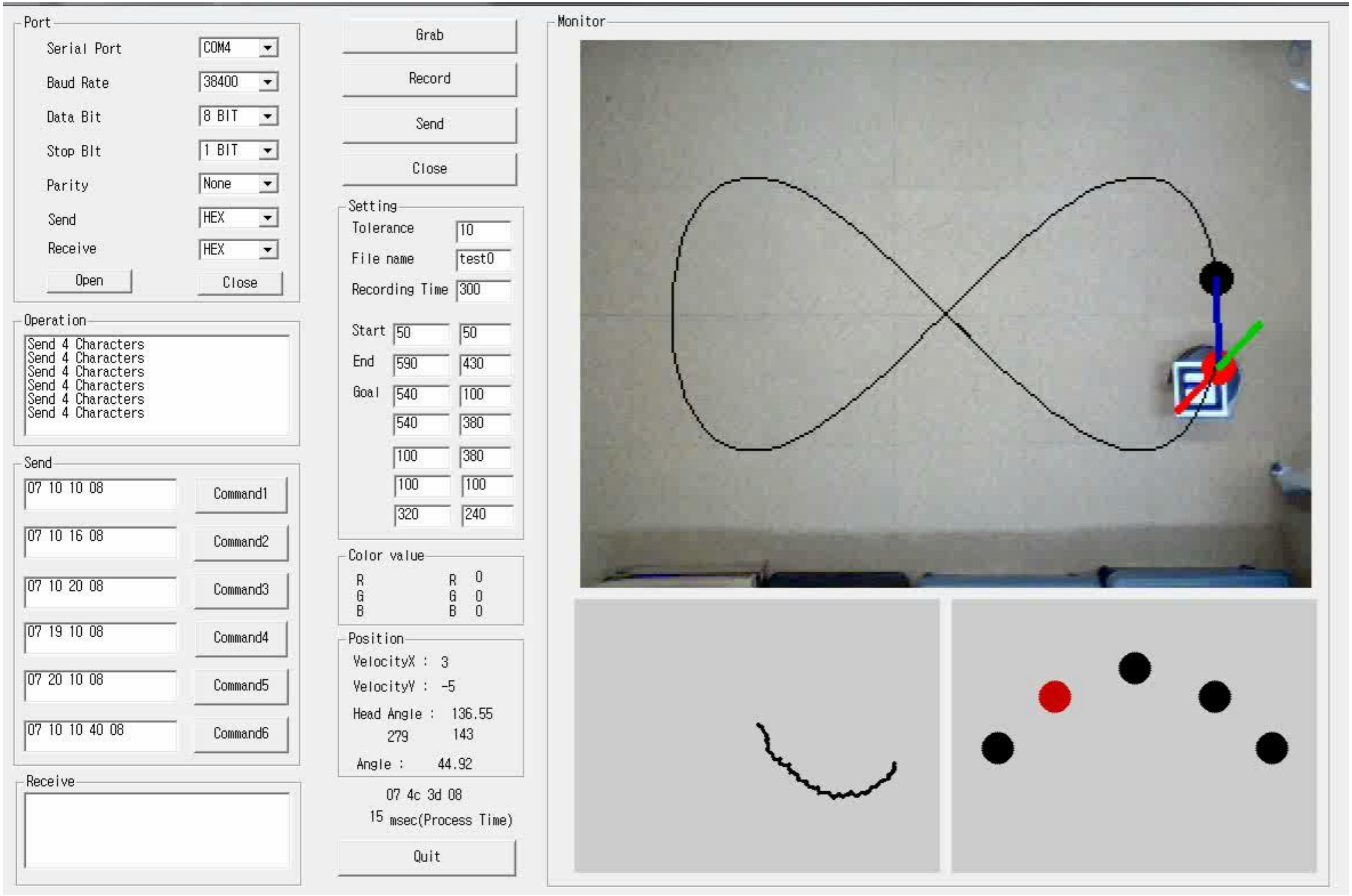
- The embedded control module was based on the Raspberry Pi single-board computer with a Broadcom BCM2835 system on a chip (SoC), a Video Core IV GPU, 512 MB of RAM, and a 16 GB SD card.

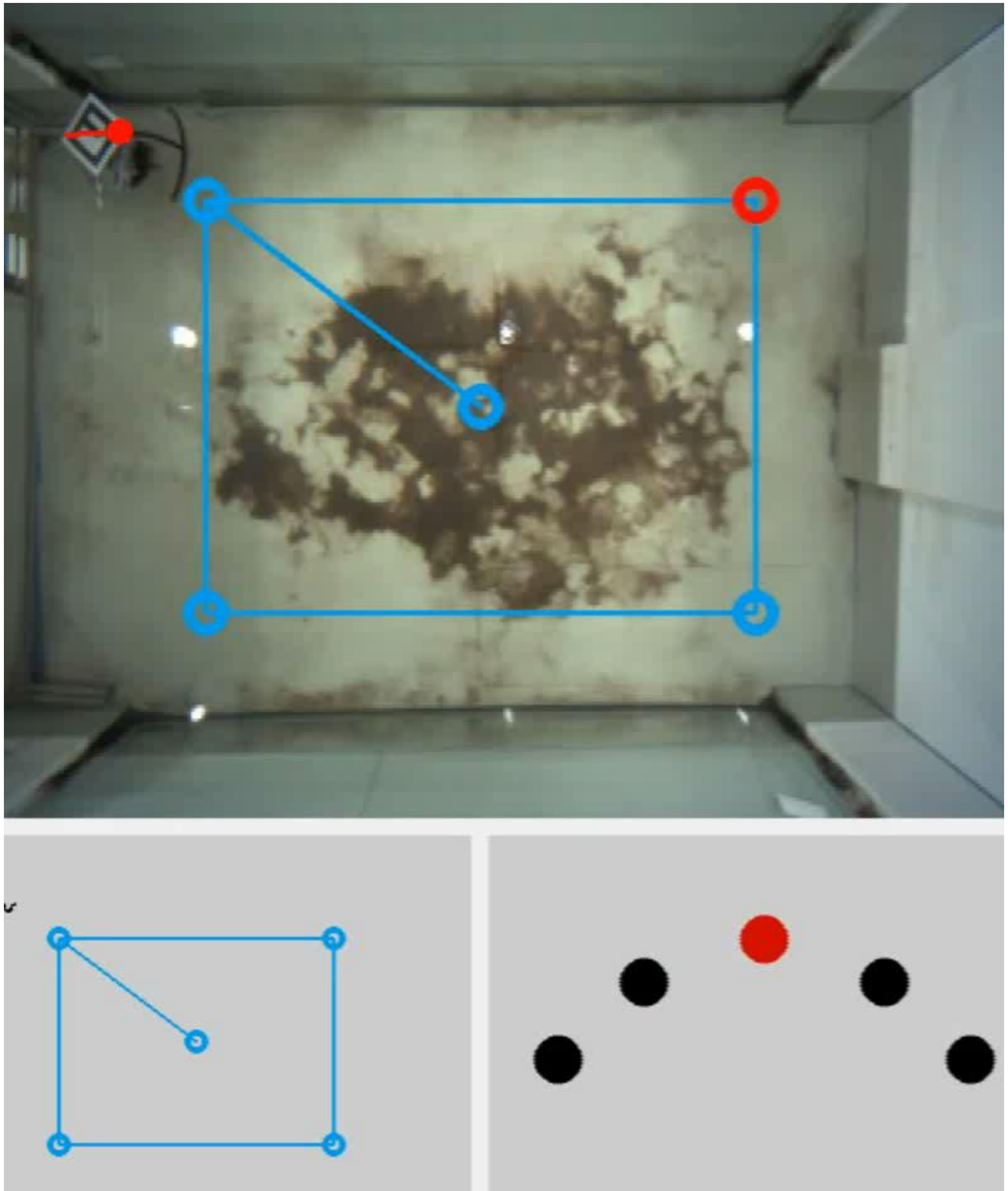
- This embedded module was connected to a servo motor which moved the stimulation semi-cylinder, as well as a 2600 mAh Li-Po battery. Altogether, the device weighed 171.5 g, with the embedded control module weighing 85 g and the battery 86.5 g.

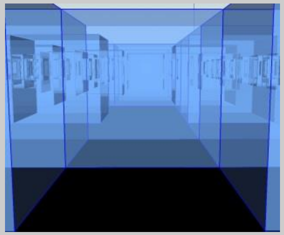
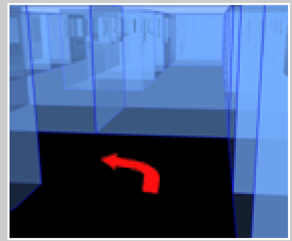
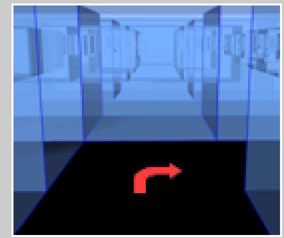
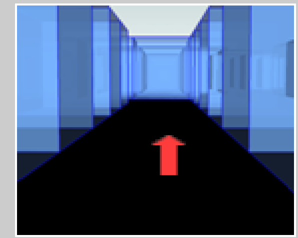
- The controller unit received an angular value to control the servo motor, thus rotating the black semi-cylinder through $\pm 36°$ with respect to its body axis, from the PC control software via a Wi-Fi connection.

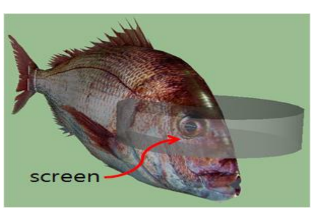
Literature survey & Preliminary experimentation

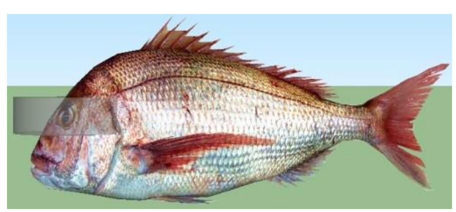



Port
Serial Port
COM4
Baud Rate
38400
Data Bit
8 BIT
Stop BIt
1 BIT
Parity
None
Send
HEX
Receive
HEX
Open
Close
Operation
Send 4 Characters
Send 4 Characters
Send 4 Characters
Send 4 Characters
Send 4 Characters
Send 4 Characters
Send
07 10 10 08
Command1
07 10 16 08
Command2
07 10 20 08
Command3
07 19 10 08
Command4
07 20 10 08
Command5
07 10 10 40 08
Command6
Receive
Grab
Record
Send
Close
Setting
Tolerance
10
File name
test0
Recording Time
300
Start
50
50
End
590
430
Goal
540
100
540
380
100
380
100
100
320
240
Color value
R
G
B
R 0
G 0
B 0
Position
VelocityX : 3
VelocityY : -5
Head Angle : 136.55
279 143
Angle : 44.92
07 4c 3d 08
15 msec(Process Time)
Quit
Monitor



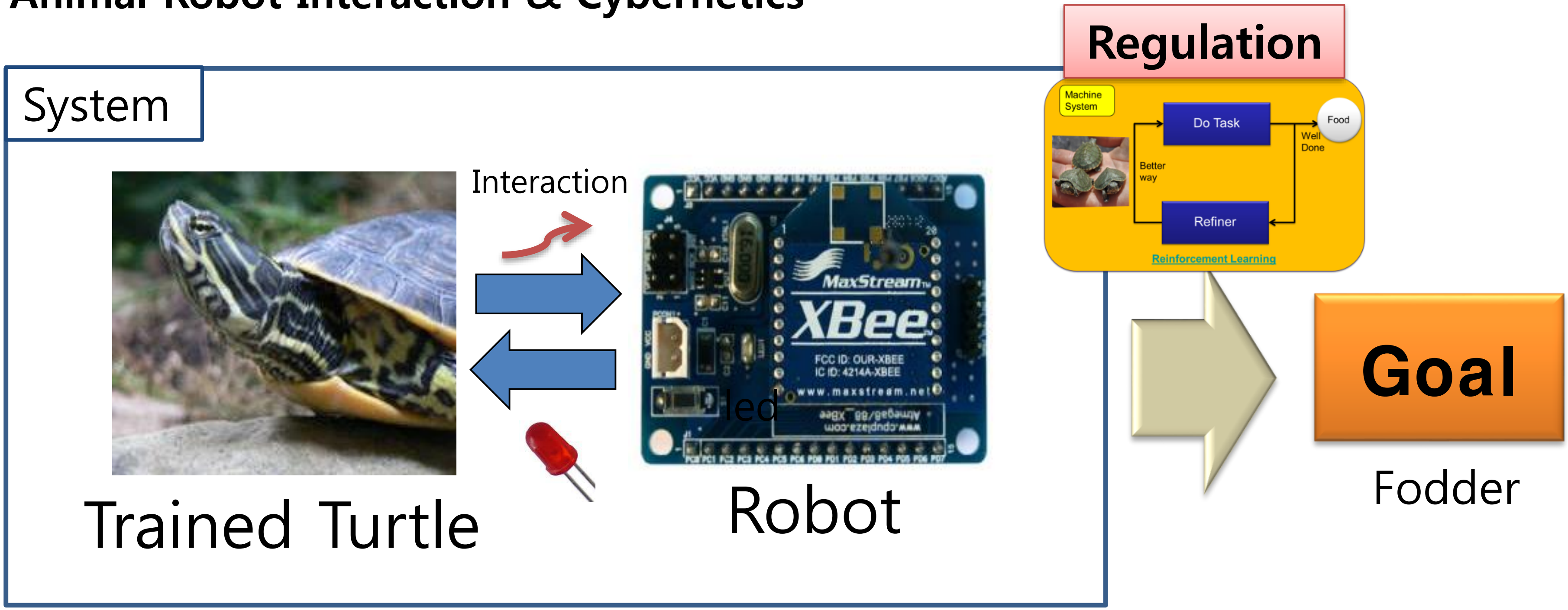
	Stop	Left	Right	Forward
View				
Screen				





CMSS
Computational Mechanics
Structural Systems

Animal Robot Interaction & Cybernetics



특정 자극(Red Light)을 따라가면 보상(먹이)를 주는 강화 학습을 통해 거북이를 훈련

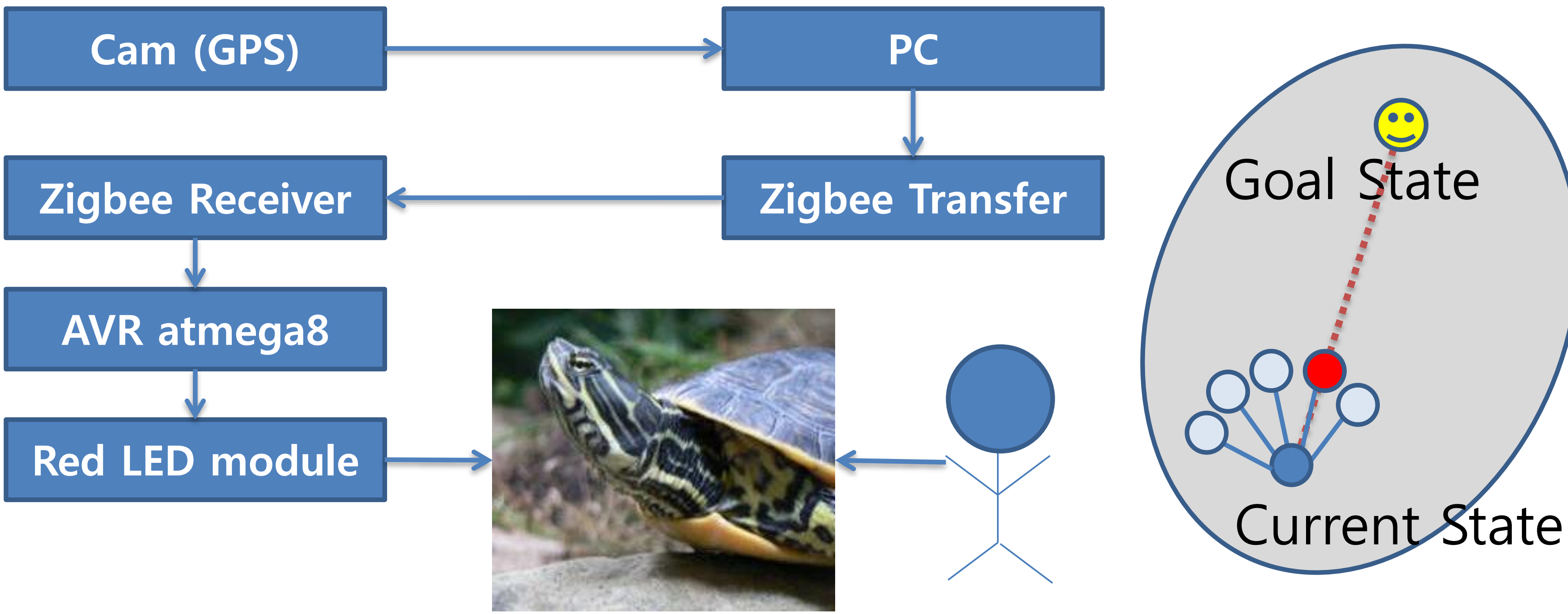
자극 (Red Light) 을 control 할 수 있는 로봇을 거북의 등에 부착

Turtle은 Robot의 자극(Red Light)을 통해 서로 interaction 하면서 보상(먹이)을 획득

위 시스템은 반복을 통한 Reinforcement Learning을 통해 강화

무선 통신(zigbee) 기술, 위치 분석(Color tracking) 기술,

목표 추적 기술(Line of sight Guidance) 등을 이용한 거북 무선 조종 시스템



Improvement point - Turtle

- We couldn't show anatomical reason for reactive behavior among target animals.

- Until, our system require more advanced hardware technology for long range operation and precise control.

- Also, it is necessary to overcome the technical difficulties of designing a new device in order to apply the specific stimulus causing the innate behavior to other animals in other environments.

Improvement point - Carp

- We couldn't construct active stimulation device.
  - ✓ Outdoor test
  - ✓ Adjust the magnitude of stimuli
  - ✓ Etc.