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Monitored and controlled underwater scissor arm manipulator using Pixy camera

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Underwater vehicle manipulator system (UVMS) generally consists of a camera unit and robotic manipulator. Its main function is to replace human work in underwater manipulation tasks. Most commercially available manipulators are not designed for autonomous underwater vehicle (AUV) because the vehicle does not have sufficient power supply to drive these manipulators which are electro-hydraulically driven. A proposed solution is to invest in development of low power underwater manipulator to deepen studies in AUV. Thus, this research has an objective of developing an underwater manipulator for small scale AUV. In this research, the manipulator is used in an object recovery task. An acrylic scissor arm which is electro-mechanically driven is used as manipulator in this research. Permanent magnets are used as its end effector. A Pixy CMUcam5 vision sensor is paired with this manipulator to navigate the AUV and control the manipulator. The usage of planar pressure housing helps in reducing light refraction effect of underwater environment that may affect the sensor's accuracy. From the simulation done using Solid Works, it is found out that type 316L stainless steel is the best choice for the manipulator developed. To evaluate the performance of the UVMS developed, a series of tests are carried out. Based on the results obtained, it is known that the system has high speed and consistency with minimum time delay between input and output. As long as an object has distinct colour signature from its background and its surrounding is clear and well illuminated, the Pixy vision sensor can detect that object regardless of the distance between the sensor and the object.

[**Keywords:** Underwater vehicle manipulator system; Autonomous underwater vehicle; Pixy CMUcam5 vision sensor]

Introduction

Underwater vehicles are often used in maritime industry to perform underwater tasks. As for object manipulation tasks, an underwater vehicle manipulator system (UVMS) is usually required to be installed at the vehicle. Typical object manipulation tasks include valve manipulation on an underwater panel, underwater object recovery, pipeline inspection and maintenance of underwater instruments or facilities[1,3]. These underwater manipulation tasks are typically carried out using manned submersibles or remotely operated vehicles (ROVs).

Manned submersibles have an advantage of having the robotic manipulator's operator in direct view of the object to be manipulated which eases the manipulation process, but with the risk of placing the operator in a hostile environment[4]. The second option is deploying ROV which is an unmanned underwater vehicle that can be controlled through an umbilical cord connecting the vehicle and the operator on a surface vessel. In this case, the operator is not placed in hostile environment anymore, but the operator still will experience heavy fatigue in operating the manipulators. Besides, the ROV itself which is usually large in size, requires a vessel with heavy crane to deploy it, an umbilical management system to handle its umbilical cord and dynamic positioning to keep the ROV stationary while it is performing manipulation tasks. Thus, researchers have directed their focus towards automating underwater vehicles that lead to the design of autonomous underwater vehicle (AUV). As its name implies, this vehicle does not require human control, thus it is free from umbilical cord management problem which is faced by ROV. Thanks to its small size, an AUV can be deployed easier and faster than the other two options as it does not require heavy crane to deploy it. However, AUV is not usually used for underwater manipulation purpose as the research on application of UVMS on AUV only has a young history.

This research emphasizes the development of underwater manipulator and its interaction with Pixy camera for its navigation. Problems that pose as obstacles on the progress of research are identified as follows:

1. Limited power supply for manipulator

Since manipulator in this study is meant to be designed for small size AUV, the low power battery used in that vehicle is used for operating the manipulator. Thus, manipulator's design which requires a high power supply such as pneumatic or hydraulic robotic arm is not applicable. The manipulator must be able to be driven by the battery and still does not fall short to those robotic arms in terms of object manipulation ability (Fig. 1).

2. Effect of light refraction on Pixy CMUcam5 sensor operation

Light rays travel from water medium into AUV pressure hull and finally into air before entering the vision sensor. During that process, light rays are bent at air-hull material and hull material-water interfaces[5], affecting image formation geometrically. In underwater manipulation tasks, it is necessary for the vision sensor to obtain an object's precise position for the manipulator to reach that object's position. The effect of light refraction will disrupt the sensor's accuracy and affect manipulator's performance.

Literature review

Refraction is the bending of light as it passes from one transparent substance into another[6]. When light enters a medium from another, its speed changes. This change in its speed causes light ray to change its direction. The amount of bending depends on change in speed of light and angle of incident ray. The more a substance speeds up or slows down light, the more the light ray will bend. If light enters a medium at a greater angle, the amount of bending will be greater. The ability of a medium to bend light is referred to as refractive index (n). It is the ratio between the velocity of light (c) in free space and its velocity v in a particular medium[6]:

$$n = \frac{c}{v} \qquad (1)$$

Each medium has its own unique refractive index value. For example, air has refractive index of 1 while water has refractive index of 1.33. Snell's law relates incident angle (θ_1) and refraction angle (θ_2) such that:

$$n_1 \times \sin\theta_1 = n_2 \times \sin\theta_2 \qquad (2)$$

Where n is the refractive index for material 1 and material 2. When n_1 is greater than n_2, refraction angle is always larger than incident angle. When refractive index of both mediums is the same or incident angle is 0°, no light refraction will occur[6]. For underwater vision, it is important to compensate for light refraction to have an accurate vision.

In computer vision, camera is the most important element as it provides visual feedback to the processor for decision making. It should have a sufficiently large field of view to provide vision on area of surveillance. There are two common types of camera used in computer vision: Charge-coupled device (CCD) and complementary metal-oxide semiconductor (CMOS) as shown in Figure 2. Both convert light into electricity using photoelectric effect. CCD camera completes this task by using MOS capacitors to capture and store charge, then moving the charge one pixel at a time until it reaches an amplifier to convert the charge into voltage[7,8]. CMOS differs from CCD in such that CMOS converts charge into voltage immediately at the pixel. The voltages are then read with column and row selectors[8].

Different techniques have been implemented to obtain desired visual on an area of interest. Jos´e Gaspar has used a combination of CCD camera and convex mirror[9]. The camera is pointed upwards looking at the spherical mirror where images are reflected by the mirror into the camera. This techniques allows camera to have a 360° vision on its surrounding. 360° vision also can be achieved without using convex mirror. Josep Bosch used an omnidirectional multi-camera system (OMS) based on

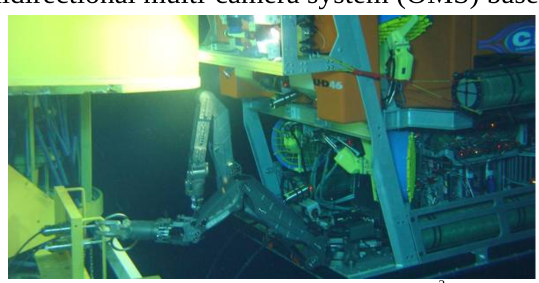


Fig. 1 — ROV with robotic manipulator[2]

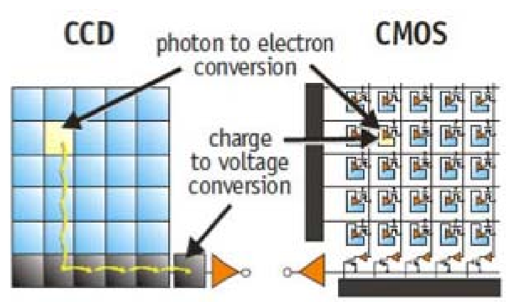


Fig. 2 — CCD and CMOS cameras' charge to voltage conversion[8]

a commercially available six-camera system[10]. Images captured by each camera are later combined to obtain a panoramic image, thus achieving a large field of view. In a study conducted by Mark R. Shortis, a CCD camera array was used for computer vision[11]. By comparing images taken by those cameras, dimension of an object of interest can be estimated based on separation distance between the cameras. For other research such as the study conducted by Homer H. Pien, only a forward pointing camera was used[12]. This setup allows the vision sensor to have a vision over a large distance, and thus is effective in object searching operation (Table 1).

Based on these research, it can be inferred that the combination of camera and convex mirror and the usage of omnidirectional multi-camera system are suitable for environment mapping as it provides wide field of view. Camera array or front pointing camera will perform better in object searching and navigation as they are capable to provide vision over great distance.

Images captured by vision sensors are required to be processed to extract desired information. Hence, a processor is necessary where all image processing work will be performed. In a study conducted by Michael John Poretti, he connected camera to a laptop where all image processing tasks were completed[8]. This method has an advantage such that high processing power of a laptop can be used for processing all the images and videos taken. Thus, image processing process can be completed in a short time. However, Senthilkumar stated that portability of computer is limited by its high power consumption[13]. He proposed that the solution for that problem is by using embedded system. In his study, he used Raspberry Pi system which has processing power similar to computer for image processing. His solution solved the portability problem without compensating to processing power. Since image processing consumes most resources of a processor, other resources available in the Raspberry Pi may have wasted if it is used to deal with images. To solve that issue, Islam Mohamad proposed the usage of Pixy CMUcam5 which consists of a camera and a processor that has resources solely for image processing[14]. Table 2 shows the comparison between types of processors.

Based on the comparison, Raspberry Pi would be the best choice for image processing as it has high processing power and high portability. If budget is a concern, Pixy CMUcam5 can be used instead. Although it has lower processing power, its resources are sufficient for image processing tasks.

Image processing technique

Before any manipulation task can be performed, a system needs to identify the position and sometimes orientation of an object of interest by extracting information out of captured images. This process is known as image processing. There is different approach in other studies in recognizing an object. In Jos´e Gaspar's research, he made his robot to be able to identify its current location by comparing current images to previously acquired views of the location[9].

Table 2 — Comparison between processors used for image processing

Researcher	Processor	Advantage	Disadvantage
Michael John Poretti [8]	Laptop	High processing power	Low portability, high power consumption
Senthilkumar [13]	Raspberry Pi	High processing power, portable	Wastage of resources, expensive
Islam Mohamad [14]	Pixy CMUcam5	Portable, no wastage of resources, cheap	Lower processing power

Table 1 — Comparison of techniques used in computer vision

Researcher	Methods used	Advantage	Disadvantage
Jos´e Gaspar [9]	Combination of CCD camera and convex mirror	360° vision coverage	Can provide vision over short distance around camera only
Josep Bosch [10]	Omnidirectional multi-camera system	360° vision coverage, Able to provide vision over great distance	Consumes a lot on processor's resources as image processing is required for all 6 cameras
Mark R. Shortis [11]	CCD camera array	Allows estimation of an object's dimension	Consumes a lot on processor's resources as image processing is required for all cameras
Homer H. Pien [12]	Front pointing camera	Able to provide vision over great distance	Limited field of vision

On the other hand, Homer H. Pien used three levels of image processing algorithms to save computation time[12]. The Level-1 algorithm provides low accuracy, but very rapid range estimate. In Level-2, a medium accuracy range estimate is produced by extracting and measuring the radius of the target and comparing it against the known target radius. Level-3 algorithm performs high accuracy range and orientation estimation. These algorithms are carried out in incremental order so that processor can halt image processing process if object of interest is not in the image taken, thus saving computation time. In research conducted by Akihisa Ohya, current image taken was compared with 3D rendered model[15]. In both approaches taken by Akihisa Ohya and Jos´e Gaspar, edges are extracted from image captured and are compared with the edges extracted from expected image using extended Kalman filter.

Another method that can be used to recognize an object is by colour hue image processing. According to Zachary Sabey, an image is typically extracted into a RGB scheme that contains values of primary colours from 0 to 255, for image processing based on colour hue[16]. The three colour schemes can then be manipulated to extract desired information. In his study, Pixy CMUcam5 was used. This vision sensor extracts information from images through colour hue image processing. The information extracted is then transferred to main processor for decision making. The Pixy camera was also used by Islam Mohamad, Li Dang and Seokju Lee in their respective studies to identify objects through colour codes[14,17,18].

Table 3 compares the techniques used in image processing. In the case where object of interest has a vibrant colour, colour hue image processing is advised to be used as this method uses simpler algorithms. In other cases, edge detection technique should be used.

Refraction calibration

When a camera operates under water, light ray has to travel between mediums before reaching camera. The difference in density between the mediums causes refraction of light which distorts the accuracy of the vision sensor. According to Michael John Poretti, refraction causes several negative effects: Unequal magnification and reduced field of view[8]. The unequal magnification becomes more prominent towards the edge and causes pincushion distortion which is a type of radial distortion. Another type of radial distortion is known as barrel distortion that causes decreasing magnification towards edge of an image. Barrel distortion is always present in cheap cameras with wide lens (Fig. 3).

Two most common housing used for underwater camera are planar and hemispherical housings. Planar housing is easier to be created but it is prone to pincushion distortion and has reduced field of view. The only incident angle for light ray to experience zero distortion is zero. Hemispherical housing takes advantage of this property as it only allows perpendicular light rays to enter the camera. The hemispherical housing is however difficult to be manufactured and the optical centre of camera must be placed at the centre of hemispherical housing which is mechanically difficult to do so[8].

Michael John Poretti chose planar housing in his research as he claimed pincushion distortion will help neutralize the barrel distortion introduced by cheap camera lenses[8]. Josep Bosch however chose to use hemispherical housing due to the severe reduction in field of view caused by planar housing[10]. In a study

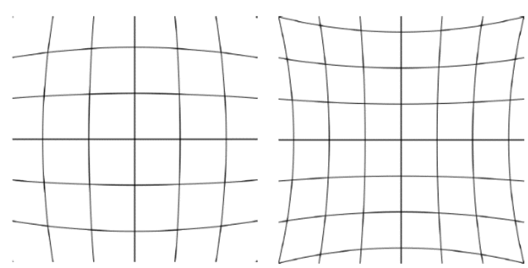


Fig. 3 — Radial distortions. Left-Barrel, Right-Pincushion[8]

Table 3 — Comparison between image processing techniques used

Researcher	Methods used	Advantage	Disadvantage
Jos´e Gaspar [10] Homer H. Pien [12] Akihisa Ohya [14]	Edge detection	Flexible as it can be used in every occasion	Location of edges might be off due to Gaussian smoothing
Zachary Sabey [15] Islam Mohamad [16] Li Dang [17] Seokju Lee [18]	Colour hue	Higher accuracy	Only applicable when colour codes are available on object of interest

conducted by Mark R. Shortis, a calibration frame which is an open cuboid as shown in Figure 4 was used for refraction calibration by measuring the location and orientation of the frame using camera[11].

Another technique was proposed by Anne Jordt-Sedlazeck where she introduced an algorithm to map a pixel to the ray it images[19]. With this method, distortion caused by planar housing can be eliminated.

Based on the Table 4, refraction can be calibrated mathematically (pixel-to-ray mapping and usage of calibration frame) or mechanically (usage of planar housing or hemispherical housing). If high accuracy is required in computer vision, mathematical solutions will be the suitable choice. Else, mechanical solutions will be more suitable as they are easier to implement.

Robotic Manipulator

Underwater manipulation operations mainly consist of four tasks: Navigation, grasping, transportation and deployment. Aside from navigation, all other tasks require usage of a manipulator. Most manipulators are designed for ROV not AUV because AUV cannot supply enough power to operate the manipulator which is electro-hydraulically driven. The operation of that manipulator also will generate noises which can affect AUV sensors' accuracy[20].

Most underwater vehicles today equip themselves with a multi-link robotic manipulator. For example, Patryk Cieslak equipped his GIRONA500 AUV with a 4 DOF 2 link robotic arm in his study[21]. He derived Jacobian matrix and used inverse kinematics for manipulator control. Several tasks are implemented in the kinematic controller: End effector position task to control end effector's position, end-effector orientation task to control attitude of end effector to avoid gimbal lock problem, end effector configuration task which is a combination of position and orientation tasks, joint saturation task to prevent joints from reaching limits, and vehicle yaw attitude task to control vehicle yaw attitude. In another study conducted by Enrico Simetti, task prioritizing was proposed where task with higher priority is executed first before task with lower priority so that one task will not interfere with another[22]. Enrico has listed out manipulation tasks with decreasing order in terms of priority as follows:

1. Joint limits avoidance
2. Dexterity (singularity prevention)
3. Camera object centering
4. Horizontal attitude
5. Vehicle position control
6. Arm end effector position control
7. Minimization of arm movement
8. Minimization of vehicle movement

All higher priority tasks are related to safety of the system (joint limits, vehicle distances, horizontal attitude) or are needed to enable the system to actually execute the manipulation mission (manipulability, camera object centering). Safety measures must be prioritized first before any manipulation operation can take place.

Some underwater vehicles use a dual arm manipulator. For example, Jee-Hwan Ryu and Signe Moe use two robotic arms in their respective study[23,24]. The two manipulators are used as master-slave system where only one manipulator will be performing manipulation tasks. Another arm moves in

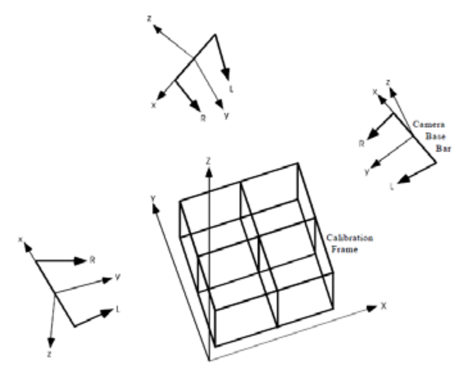


Fig. 4 — Calibration of the cameras and camera base bar using a calibration frame[11]

Table 4 — Comparison between refraction calibration techniques

Researcher	Methods used	Advantage	Disadvantage
Michael John Poretti [8]	Planar housing	Easy to be manufactured	Presence of pincushion distortion, reduced field of view
Josep Bosch [10]	Hemispherical housing	No distortion	Hard to be manufactured, hard to identify centre point of housing
Mark R. Shortis [11]	Calibration frame	Able to calibrate in various environment that has different refractive index	Long calibration time
Anne Jordt-Sedlazeck [19]	Pixel to ray mapping	No distortion	Complex algorithm

a way such that it cancels the force exerted by master arm on vehicle[23,24]. This system eases underwater vehicle in stabilizing its horizontal attitude as there are less forces acting on it. Dual arm manipulator has an advantage over single arm manipulator in a sense that dual arm manipulator can move faster single arm manipulator. Slow motion is essential for single arm manipulator to minimize the force acting on underwater vehicle.

In 2016, students in Cornell University developed an underwater manipulator than differs from other commercially available manipulators as shown in Figure 5. The manipulator designed consists of a custom pneumatic linear piston connected to a scissor arm. At the end of the scissor arm is an array of electromagnets that can be turned on and off to magnetically grab an object[25].

Based on comparison in Table 5, if manipulation tasks cover a wide area, both single and double multi-link manipulators can be used. If the underwater vehicle has available space on it, double manipulator will be a better choice as it allows faster arm movement. Since UVMS is always kinematic redundant because necessary DOFs are provided by the vehicle itself, scissor arm can be used in manipulation task even though it has small workspace as it has only 1 DOF.

Methodology

Since BlueROV1 does not have a downward facing planar housing, a box is developed to contain this sensor. The Pixy vision sensor's pressure housing is made of a box with a lid which are both 3D printed using ABS material, and sealed with a planar acrylic base with silicone gel. The sensor is mounted in such a way that it receives underwater image through the transparent base. As the manipulation target in this study is always beneath the AUV, pointing the sensor towards negative z-axis enables the sensor to detect that object. A pair of rubber rings are used on the box lid to create a watertight box. Both the box and its lid are painted with flex seal liquid rubber to prevent water from entering into the box from pores between the ABS layers in the box and lid. A pair of supportive arms are added to install the housing on the AUV. The developed pressure housing for the vision sensor is shown in Figure 6.

Weight: 594 g
Dimension: 15.1 cm x 12.1 cm x 29.5 cm

Robotic Manipulator

As stated above, commercially available underwater manipulators are mostly electro-hydraulically driven. Thus, they have high operating power and generate noises which can affect sensors' accuracy[20]. An AUV where power is supplied by

Fig. 5 — Underwater manipulator designed by Cornell University [25]

Table 5 — Comparison between techniques used in manipulator design

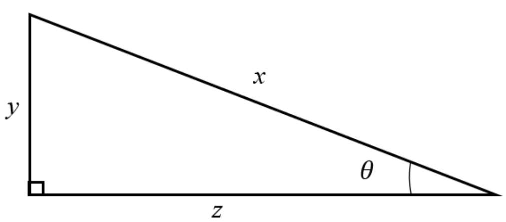
Researcher	Methods used	Advantage	Disadvantage
Patryk Cieslak [21] Enrico Simetti [22]	Single multi-link manipulator	Wide workspace	Very slow arm movement
Jee-Hwan Ryu [23] Signe Moe [24]	Double multi-link manipulator	Fast arm movement, wide workspace	Consumes space on underwater vehicle
Students in Cornell University [25]	Pneumatically actuated scissor arm	Simple design	Small workspace

Fig. 6 — Pixy sensor pressure housing with supportive arms

battery fitted in it, is incapable to supply enough power to operate those manipulators. Hence, this research discussed about the design of a manipulator which is electromechanically driven to lower its operating power.

A scissor arm which has only 1 DOF is used in this research. Its insufficient workspace is not much of a concern as AUV itself can compensate this problem by adjusting its position or orientation. Extension is achieved by applying pressure to the outside of a set of supports located at one end of the mechanism, elongating the crossing pattern. The arm is made of acrylic to make it light weight and resists corrosion. The scissor arm is actuated using rack and pinion which are driven by a DC motor (JGB37-520) for arm extension and retraction. The rack and pinion are 3D printed using PLA material and are fit inside a housing which are made from PLA as well. To allow the DC motor to operate under water, its inner space is filled with petroleum gel before it is inserted into a PVC pipe connected to a pair of PVC pipe caps that are sealed using silicone gel.

In manipulation tasks, the scissor arm will always fully extend its arm for easier control. The AUV will then adjust its position to move manipulator's end effector towards location of an object of interest. By setting desired manipulator fully extended length at 40 cm and setting number of scissor arm crossing support at 4.5 (4 supports at length *x* and 1 support at 0.5*x*), the length of each scissor arm support, *x* and its horizontal travel distance to reach desired height, *z* is determined as follows:



$y = Vertical\ extended\ length\ of\ each\ crossing\ support$

$$y = \frac{40}{4.5} = 8.889cm$$

Setting θ at 45°, $\sin\theta = \frac{y}{x}$

$$\sin 45° = \frac{8.889}{x}$$

$$x = 12.571cm \approx 12.6cm$$

$$\tan\theta = \frac{y}{z}$$

$$\tan 45° = \frac{8.889}{z}$$

$$z = 8.889cm \approx 8.9cm$$

Manipulator End Effector

A manipulator end effector's main task in this study is to retrieve an airflow training golf ball that has iron cables wrapped around it as shown in Figure 7. To minimize stress exerted on the manipulator arms, the end effector must have a light weight. Thus, its design is kept simple. Several magnets are tied together on a 3D printed ABS base with cable ties to form the end effector. The magnets will attract the cables wrapped around the golf ball towards itself. This end effector is connected to the manipulator arm via an acrylic plate.

Mechanical assembly

The assembly of the manipulator is shown in Figure 7. The installation of manipulator and camera pressure housing on the AUV is also shown in Figure 7. Arrow in Figure 8 shows the downward facing direction of the AUV.

Weight: 1 kg

Dimension: 32 cm x 9.6 cm x 34 cm

Fig. 7 — Assembly of manipulator

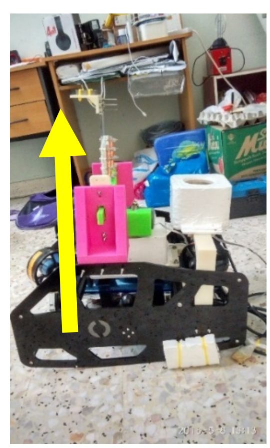


Fig. 8 — Installation of UVMS on AUV

Results and Discussion

Maximum load and depth analysis

ABS is chosen to be analyzed for rack and pinion housing instead of PLA as used in this research because library for PLA material is not available in SolidWorks. Stainless steel and aluminum alloy are chosen as candidates for manipulator's material because of their high corrosion resistance that is suitable for marine applications. Among all types of stainless steel, type 316L stainless steel is selected to be analyzed as it exhibits better corrosion resistance and is stronger at elevated temperatures[29]. On the other hand, 5454-H112 aluminum alloy is manufactured through strain hardening process that gives the alloy an increase in mechanical strength and hardness[30]. Along with its high corrosion resistance, its mechanical properties make it suitable for underwater application.

From Table 6, it is clear that all parts have the highest maximum load value when type 316L stainless steel is applied to them, while they have the minimum load value when ABS is applied. Plastics have shown a lower maximum load values than metals due to their weak yield strength. Among the maximum load values, rack and pinion housing has the minimum value. Any load more than this value will cause this part to undergo plastic deformation. So, the maximum load that can be carried by this manipulator is the same maximum load value that can be applied on the rack and pinion housing. However, this value may be changed depending on the design of end effector. For this research, permanent magnets are used in the end effector. So, the maximum load it can carry depends on the magnetic field strength generated by the magnets. To have the best performance, type 316L stainless steel is the best choice for this manipulator since it has the highest maximum load values among all materials analysed. If this manipulator is intended to only carry a small object that has small weight, plastic may be used for this manipulator as a cheaper solution (Table 7).

The maximum water depth can be calculated from the maximum hydrostatic pressure as follows:

$$P = P_{atm} + \rho g h \tag{3}$$

$$h = \frac{P - P_{atm}}{\rho g}$$

$$h = \frac{P - 101325}{(1000)(9.81)}$$

Based on the results obtained, there is a significant difference between the maximum hydrostatic pressure values between plastics and metals in which the metals can withstand greater hydrostatic pressure than plastics. Similar with maximum load analysis, the maximum hydrostatic pressure value can be found on parts made from type 316L stainless steel, while the minimum value can be found on parts made from ABS. Since rack and pinion housing has the lowest maximum depth value for all materials, its maximum depth values are considered as the maximum depth can be travelled by the whole manipulator as the hydrostatic pressure causes the housing part which is an essential part in this manipulator to deform permanently at greater depth.

To conclude, type 316L stainless steel has the best performance in terms of maximum load that can be carried and maximum water depth that can be travelled. Thus, this material is the best choice for the manipulator for underwater applications. However, if this manipulator is used to carry a load that has light weight in shallow water, cheaper options such as the ABS may be used to manufacture this product as long as the weight and depth values do not exceed the material's limits.

Object recognition limit test

Based on Table 8, the ability of Pixy vision sensor in recognizing object under water declines with

Table 6 — Maximum load can be applied on manipulator parts

Material	Maximum load /N		
	Rack and Pinion housing	Scissor arm part	End effector
ABS	118.1	2209.0	197.9
Acrylic	185.1	2511.0	308.2
5454-H112 aluminium alloy	513.7	6919.0	853.5
Type 316L stainless steel	697.7	9193.0	1153.0

Table 7 (A) — Maximum hydrostatic pressure can be withstanding by manipulator parts

Material	Maximum hydrostatic pressure /kPa		
	Rack and Pinion housing	Scissor arm part	End effector
ABS	1635	20680	22300
Acrylic	3962	45530	31030
5454-H112 aluminium alloy	10740	112700	73830
Type 316L stainless steel	13610	114200	75950

distance in non-illuminated environment. The light green boxes in the images represent the colour signature detected by the sensor. On the other hand, the vision sensor is able to recognize an object regardless the distance from that object under an illuminated environment. This proves that this vision sensor works better in clear and illuminated surrounding.

When an object has similar colour with its background, the vision sensor fails to recognize that object no matter how close it is to the sensor even though the surrounding is well illuminated as shown in Table 9. This shows that this vision sensor can detect an object only if it has distinct colour signature from its background. From the images, it is observed that distortions as shown in Figure 8 are not significant in the images recorded, thus justifying the usage of planar housing in neutralizing light refraction effect in under water environment.

In summary, the Pixy vision sensor can recognize object under water only if that object has distinct colour from its background and its environment is clear and well illuminated. If both conditions are met, the sensor can recognize an object no matter how far that object is from the sensor as long as it is still visible in the sensor's vision.

Table 7 (B) — Maximum water depth that can be travelled by manipulator parts

Material	Maximum water depth /m		
	Rack and Pinion housing	Scissor arm part	End effector
ABS	156.3	2097.7	2262.9
Acrylic	393.5	4630.9	3152.8
5454-H112 aluminium alloy	1084.5	11477.9	7515.7
Type 316L stainless steel	1377.0	11630.9	7731.8

Table 8 — Object recognition test using green airflow training golf ball

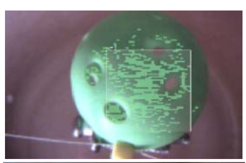
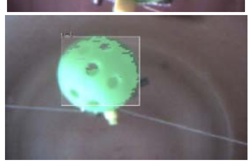
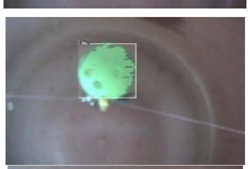
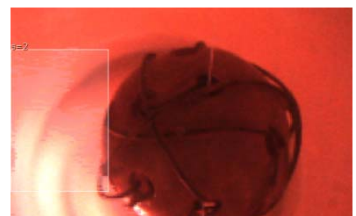
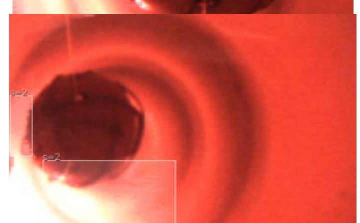
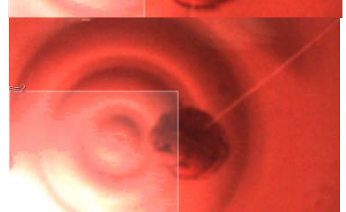
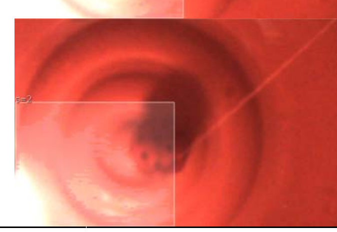
Distance from sensor/ cm	Without illumination	With illumination
5		
15		
25		
35		
45		

Table 9 — Object recognition test using red airflow training golf ball

Distance from sensor/ cm	With illumination
5	
15	
25	
35	
45	

Manipulator extension and retraction test

From the results in Table 10, manipulator's extension length has little deviation between the tests. On the other hand, the retraction length has more significant deviation in its values between tests. This shows that this manipulator has better consistency during extension process than during retraction process as suggested by their standard deviation values. Retraction lengths have larger standard deviation value, implying that it has lower consistency.

Manipulator's maximum extension length: 40.2 cm

Manipulator's minimum retraction length: 20 cm

Since the manipulator always extends and retracts its arm fully during manipulation operation, all values from extension lengths have high accuracy at average of 98.2% compared to retraction length at average of 74.2%. This difference is most probably caused by act of gravity. The direction of scissor arm extension is the same as direction of gravity while the direction of arm retraction is opposite to the direction of gravity. Thus, gravity helps the arm to achieve its maximum length during extension by pulling it downwards. On the other hand, DC motor has less force to retract the scissor arm due to resistance from gravity.

To conclude, this manipulator has better consistency and accuracy in terms of arm's length during extension process. To enhance manipulator retraction length's consistency and accuracy, an underwater limit switch may be used to act as an on/off switch for manipulator operation so that the manipulator is able to achieve desired lengths consistently.

Input and output time delay test

From Table 11, it can be clearly seen that this UVMS developed only need little time of average 0.41 s to generate output from the time it receives an input. A low value of standard deviation also suggests that the time delay has high consistency. A low time delay value implies that the system can rapidly react to changes in input to accurately navigate AUV and control manipulator.

Object recovery test

Based on the results in Table 12, the UVMS successfully retrieved the golf ball in all the tests, suggesting a high functionality in the system. In both cases, the UVMS is able to retrieve the golf ball in less than 30 s.

Table 10 — Measured manipulator's extension and retraction lengths

Test	Extension length /cm	Retraction length/ cm
1	39.20	25.40
2	39.60	26.20
3	39.50	23.50
4	39.80	26.80
5	39.40	26.30
6	39.50	24.90
7	39.50	23.70
8	39.70	25.40
9	39.30	24.60
10	39.30	24.80
Average	39.48	25.16
Standard deviation	0.18738	1.084435

Table 11 — Time delay between input and output

Test	Time delay /s
1	0.40
2	0.70
3	0.30
4	0.30
5	0.20
6	0.50
7	0.40
8	0.20
9	0.60
10	0.50
Average	0.41
Standard deviation	0.166333

Table 12 — UVMS underwater object retrieval operation time

Test	Operation time /s		Successful ball retrieval
	AUV initial position near to golf ball	AUV initial position far from golf ball	
1	13.40	18.20	Yes
2	10.60	17.50	Yes
3	11.70	21.80	Yes
4	14.60	19.40	Yes
5	12.70	17.50	Yes
6	15.20	20.90	Yes
7	13.90	22.10	Yes
8	12.10	18.60	Yes
9	12.40	21.40	Yes
10	13.30	20.70	Yes
Average	12.99	19.81	
Standard deviation	1.381183	1.782913	

The time required for the system to retrieve the ball is longer for the case where AUV is initially placed far from the ball. This is because thrusters need more time to navigate the AUV over the distance towards the object's location. As the thruster speed is proportional to the distance between object and sensor, a far distance will cause the thruster to move at higher speed, increasing the likelihood of causing AUV to overshoot from that object's location.

In summary, the UVMS developed is able to perform object retrieval operation in less than 30 s, showing that it has high speed in conducting this task. To have faster operation, the AUV must position itself as close to an object's position as possible before allowing the vision sensor to finely adjust its position.

Conclusion

This paper has presented the research significance, review on previous related works, design on underwater manipulator and tests and analysis to determine the manipulator's performance. The research significance which includes the application and impact of UVMS is first discussed. UVMS is capable to replace human work in underwater manipulation tasks as it can be operated over a long period of time and is capable of reaching depths which are harmful to humans. The project scopes are also determined where the manipulator in this research is designed for object recovery task.

To identify UVMS design criteria, various techniques used by previous works in designing UVMS are reviewed. These techniques are compared with each other to clarify the difference between them. Based on the comparisons done, the design for underwater manipulator and selection of vision sensor has been proposed where 1 DOF scissor arm and Pixy CMUcam5 vision sensor will be used. The sensor will be used to navigate the AUV to an object's location and control the manipulator. Experiments are then planned to analyze performance of UVMS thus designed. Object recognition ability of Pixy CMUcam5 vision sensor has been analyzed to understand its performance under water.

Through simulation using SolidWorks, it is known that type 316L stainless steel is the best material to be applied on the manipulator designed. Using this metal, the manipulator can carry load up to 697.7 N and travel up to 1377 m from water surface before experiencing plastic deformation. If the manipulator is to be used to carry a lighter load in shallower water, cheaper options such as plastics may be opted as long as these values do not exceed the material's limits.

From the results, it is known that the Pixy sensor is able to detect an object as long as that object has distinct colour signature from its background and its surrounding is well illuminated. The manipulator designed has high consistency in terms of extension length. Due to gravity, it is hard for the manipulator to retract to its minimum length within 1 s. Nevertheless, the system has a minimum time delay between input received and output generated. The system also has high speed and never fails during tests in conducting object retrieval operation.

For future work, it is recomm ed that underwater limit switches are implemented into the system to control manipulator's length. By using this component, the manipulator will be able to reach its desired extension and retraction lengths consistently instead of using time delay to control its length that has been proven ineffective especially in retraction process. Next, there will always be a presence of blue hue in underwater images when the sensor operates in a large volume of water such as lake or ocean. As the Pixy sensor recognizes an object based on colour signature, the presence of blue hue will clearly decrease the sensor's performance in detecting object because the blue hue makes that object appears to have a different colour signature. Thus, research on real time elimination of blue hue in underwater images should be done in the future so that the sensor can operate in areas with strong blue hue.

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