SWITCHING REFERENCE IMAGE-BASED VISUAL SERVOING FOR UNDERWATER DOCKING OF AUTONOMOUS UNDERWATER VEHICLE

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by

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LIST OF ABBREVIATIONS

2D	2-Dimensional
3D	3-Dimensional
ACC	Accuracy
AFSA	Artificial Fish Swarm Algorithm
ANN	Artificial Neural Network
AUV	Autonomous Underwater Vehicle
BGOT	Balance-Guaranteed Optimized Tree
BRIEF	Binary Robust Independent Elementary Features
BRISK	Binary Robust Invariant Scalable Keypoints
CAD	Computer Aided Design
CCD	Charge-Coupled Device
CenSurE	Scale-Invariant Center-Surround
CMOS	Complementary Metal-Oxide Semiconductor
CNN	Convolutional Neural Network
DOF	Degrees of Freedom
ELM	Extreme Learning Machine
EM	Electromagnetic
ESC	Electronic Speed Controller
FAST	Features from Accelerated Segment Test
FDR	False Discovery Rate
FN	False Negative
FNR	False Negative Rate
FP	False Positive

FREAK	Fast Retina Keypoint
GA	Genetic Algorithm
GPU	Graphics Processing Unit
HOG	Histogram of Oriented Gradients
IBVS	Image-Based Visual Servoing
IMU	Inertial Measurement Unit
KLT	Kanade-Lucas-Tomasi
LARS	Launch and Recovery System
LBP	Local Binary Patterns
LQR	Linear Quadratic Regulator
LVS	Laser Vision System
MSER	Maximally Stable Extremal Regions
NMPC	Nonlinear Model Predictive Control
NRMSE	Normalized Root Mean Square Error
ODE	Ordinary Differential Equations
ORB	Rotated BRISK
PBVS	Position-Based or Pose-Based Visual Servoing
PD	Proportional Derivative
PI	Proportional Integral
PID	Proportional-Integral-Derivative
PLA	Poly Lactic Acid
POI	Point of Interest
PPV	Positive Predictive Value
PSO	Particle Swarm Optimization
PVC	Polyvinyl Chloride

PWM	Pulse Width Modulation
R-CNN	Region with Convolutional Neural Network
RED	Robust Exact Differentiator
R-FCN	Region-based Fully Convolutional Net
RGB	Red-Green-Blue
ROI	Region of Interest
ROV	Remotely Operated Vehicle
RPN	Region Proposal Network
SAUV	Solar-powered Autonomous Underwater Vehicle
SIFT	Scale-Invariant Feature Transform
SM	Sliding-Mode
SMC	Sliding-Mode Controller
SSD	Single Shot Multibox Detector
SURF	Speeded Up Robust Features
SVM	Support Vector Machine
TN	True Negative
TP	True Positive
TPR	True Positive Rate
USBL	Ultra-Short Baseline
VS	Visual Servoing

LIST OF SYMBOLS

a	acceleration
z	accumulation of error
$\delta_a(n)$	actual value for sample n
$X_{\dot{u}}$, $Y_{\dot{v}}$, $Z_{\dot{w}}$, $K_{\dot{p}}$, $M_{\dot{q}}$, $N_{\dot{r}}$	added mass due to hydrodynamics
$\mathbf{M}_{\mathrm{A}}$	added mass inertia matrix
$\dot{p}$, $\dot{q}$, $\dot{r}$	angular accelerations about x_b, y_b, and z_b respectively
p, q, r	angular velocities about x_b, y_b, and z_b respectively
B	buoyancy force of AUV
$\mathbf{f}_b^n$	buoyancy force vector with respect to n-frame
θ_h	camera field of view horizontal angle
θ_v	camera field of view vertical angle
$\mathbf{v}_c$	camera homogeneous transformation matrix
$\mathbf{K}$	camera intrinsic parameters matrix
$\mathbf{A}_{cd}$	closed-loop diving subsystem matrix
$\mathbf{A}_{ch}$	closed-loop heading subsystem matrix
c	condition number
$b(k)$	convolved biased of index k
$x(k)$	convolved pixels of index k
$w(k)$	convolved weight of index k
x_b, y_b, z_b	coordinate frame of body-fixed
x_c, y_c, z_c	coordinate frame of camera
z_{de}	coordinate frame of depth
x_d, y_d, z_d	coordinate frame of docking station
x_n, y_n, z_n	coordinate frame of NED body-fixed

x_p, y_p, z_p	coordinate frame of pool
$\mathbf{C}_{RB}(\mathbf{v})$	Coriolis and centripetal forces matrix of rigid-body for velocity vector **v**
$\mathbf{C}_A(\mathbf{v})$	Coriolis and centripetal matrix for added mass
c(·)	cosine function
$\mathbf{T}_{loss\_}$	coupling terms and environmental disturbances
ζ	damping ratio
ζ_s	damping ratio for surge speed control
ρ	density of AUV
$\mathbf{h}_d$	depth eigenvector
$\mathbf{k}_d$	depth poles vector
z_d	desired depth
$\dot{w}_d$	desired depth acceleration
w_d	desired depth velocity
L	desired label value
u_d	desired surge speed
$\delta_d(n)$	desired value for sample *n*
ψ_d	desired yaw angle
$\dot{r}_d$	desired yaw angular acceleration
r_d	desired yaw angular velocity
Z	distance between camera and target in real world
l_x	distance from center of AUV's body (o_b) to center of thruster in x-axis
l_y	distance from center of AUV's body (o_b) to center of thruster in y-axis
b_d	diving input coefficient in state space
a_{dnm}	diving parameters in state space

d1, d2, d3, d4, d5	docking markers
λ_h	eigenvalue for pure integrator of r producing ψ
$\mathbf{e}_{Pn}$	error between desired and current feature points on image plane
e	error between u_d and u
$\mathbf{T}_{\text{loss}}$	error dynamics
ϕ , θ, ψ	Euler angles of roll, pitch, and yaw with respect to n-frame
$\mathbf{\Theta}$	Euler angles vector
$\dot{\mathbf{p}}_n$	feature motion vector
$\mathbf{p}_{sw\ cn}$	feature point vector (acquired switched)
$\mathbf{p}_{cn}$	feature point vector (current)
$\mathbf{p}_{sw\ dn}$	feature point vector (desired switched)
$\mathbf{p}_{dn}$	feature point vector (desired)
$\mathbf{p}_{\text{cn new}}$	feature point vector after certain feature points are removed
$\mathbf{F}_{Pn}$	feature sensitivity matrix with respect to principal point of point $\mathbf{P}_{\text{n}}$
f	focal length
F	force
$\dot{\boldsymbol{\theta}}_f$	fractional angular motion vector
$\dot{\mathbf{p}}_{n\ f}$	fractional linear motion vector
g	gravity constant
$\mathbf{g}(\boldsymbol{\eta})$	gravity force vector of AUV
$\mathbf{f}_{\text{g}}^{\text{n}}$	gravity force vector with respect to n-frame
$\mathbf{h}_h$	heading eigenvector
b_h	heading input coefficient in state space
a_{hnm}	heading parameters in state space
$\mathbf{k}_h$	heading poles vector
$\mathbf{x}_h$	heading state variables vector

H	height of image plane
h1, h2, h3, h4, h5	homing markers
$\mathbf{P}_n$	homogeneous coordinate vector of marker in real world
$\mathbf{p}_n$	homogeneous point vector of marker in image plane
$\mathbf{D}(\mathbf{v})$	hydrodynamics damping matrix
$tanh$	hyperbolic function
$\mathbf{I}_{3x3}$	identity matrix of 3 by 3
$\mathbf{I}_{\mathrm{b}}$	inertia matrix about origin of body
I_x, I_y, and I_z	inertias about x_b-, y_b-, and z_b-axes respectively
$\mathbf{f}_u$	input force vector of thrusters
K_i	integral constant
η_l	learning rate
$\dot{u}$, $\dot{v}$, $\dot{w}$	linear accelerations on x_b, y_b, and z_b respectively
λ_c	linear controller parameter for visual servo
N_v, Z_q, M_w	linear damping force coefficients (indirect) due to hydrodynamics
X_u, Y_v, Z_w, K_p, M_q, N_r	linear damping force coefficients due to hydrodynamics
$\mathbf{D}$	linear damping matrix
$u_{eq\ d}$	linear equivalent control term for depth
$u_{eq\ h}$	linear equivalent control term for heading
u, v, w	linear velocities on x_b, y_b, and z_b respectively
ℓ	loss
$\mathbf{M}_{\mathrm{RB}}$	mass inertia matrix of rigid-body
m	mass of AUV
ω_o	natural frequency
ω_{ns}	natural frequency for surge speed control

n_f	number of frames
n_s	number of successful run
n_{nc}	number of test run with no collision
o_b	origin of b-frame
o_c	origin of c-frame
o_d	origin of d-frame
o_n	origin of n-frame
o_p	origin of p-frame
u	pixel in horizontal direction
v	pixel in vertical direction
ρ_h	pixel's height
ρ_w	pixel's width
x_n, y_n, z_n	positions with respect to n-frame
u_0, v_0	principal point of image plane
$\mathbf{P}$	probability distribution vector
v_f	processing speed
$\mathbf{P}_0$	projection matrix
K_p	proportional constant
$X_{u\|u\|}$, $Y_{v\|v\|}$, $Z_{w\|w\|}$, $K_{p\|p\|}$, $M_{q\|q\|}$, $N_{r\|r\|}$	quadratic damping coefficients (kg/s) due to hydrodynamics
$\mathbf{D}_n(\mathbf{v})$	quadratic damping matrix
$z_{n\ ref}$	reference depth
u_{ref}	reference speed input
$\mathbf{v}_{rc}$	reference velocity vector of camera
$\mathbf{v}_{rr}$	reference velocity vector of robot
ψ_{ref}	reference yaw angle

R_{ac}	reliability to avoid collision
R_t	responsiveness to trajectory
X, Y and Z	resultant linear forces on x-, y-, and z-axes
K, M, and N	resultant turning forces (moments) about x-, y-, and z-axes
R_c	robustness to current
R_{lf}	robustness to loss of target features
hr	ROI height
wr	ROI width
$\mathbf{R}_x$, $\mathbf{R}_y$, $\mathbf{R}_z$	rotation matrix about x-, y- and z-axes respectively
n	sample number
sat	saturation function
$\mathbf{s}$	sensitivity of feature motion
$\mathrm{s}(\cdot)$	sine function
$\mathbf{S}(\cdot)$	skew-symmetry matrix function
s_d	sliding surface for diving
s_h	sliding surface for heading
$\mathrm{S}(\cdot)$	softmax function
$u_{sw\ d}$	switching control term for depth
$u_{sw\ h}$	switching control term for heading
$\mathrm{t}(\cdot)$	tangent function
t	time
N	total number of samples
n_{ts}	total number of supposedly successful run
n_t	total number of test run
$\mathbf{T}_a$	transformation matrix for force and moment of actuator
$\mathbf{T}_{rci}$	transformation matrix for initial camera rotation

$\mathbf{T}_{tci}$	transformation matrix for initial camera translation
$\mathbf{J}$	transformation matrix for velocity vector of n-frame
$\mathbf{T}_{bn}$	transformation matrix of angular velocity from b-frame to n-frame
$\mathbf{T}_{c}$	transformation matrix of camera based on c-frame
$\mathbf{R}_{bn}$	transformation matrix of linear velocity from b-frame to n-frame
$\mathbf{T}_{n}$	transformation matrix of robot based on n-frame
η	tuning parameter
$\mathbf{r}_{\mathrm{g}}^{\mathrm{b}}$	vector of distances from AUV's center of origin to its center of gravity
$\mathbf{r}_{\mathrm{b}}^{\mathrm{b}}$	vector of distances from center of buoyancy to center of origin of AUV
$\boldsymbol{\tau}_{\mathrm{RB}}$	vector of forces and torques of rigid-body
$\boldsymbol{\tau}_{\mathrm{ENV}}$	vector of forces from environment
$\boldsymbol{\tau}_{\mathrm{cur}}$	vector of forces from water current
$\boldsymbol{\tau}_{\mathrm{wa}}$	vector of forces from water wave
$\boldsymbol{\tau}_{\mathrm{wi}}$	vector of forces from wind
$\boldsymbol{\tau}_{\mathrm{ACT}}$	vector of forces of thrusters
$\boldsymbol{\tau}_{\mathrm{HYD}}$	vector of hydrodynamics forces
$\boldsymbol{\tau}_{\mathrm{RES}}$	vector of restoring force
u_o	velocity constant
$\dot{x}_n$, $\dot{y}_n$, $\dot{z}_n$	velocity of surge, sway, and heave with respect to n-frame
$v_c(t)$	velocity of water current at time t
$\dot{\mathbf{\Theta}}_n$	velocity vector (angular) for n-frame
$\boldsymbol{\omega}_{\mathrm{b}}$	velocity vector (angular) of b-frame
$\mathbf{v}_b$	velocity vector (linear) for b-frame
$\dot{\mathbf{p}}_{ln}$	velocity vector (linear) for n-frame
$\dot{\boldsymbol{\eta}}$	velocity vector of n-frame

∇	volume of fluid displaced by AUV
W_a	weight of AUV
W	width of image plane

KEBOLEH-TUKARAN RUJUKAN PENGLIHATAN SERVO BERASASKAN IMEJ UNTUK DOK BAWAH AIR BAGI KENDERAAN AUTONOMI BAWAH AIR

ABSTRAK

Kenderaan autonomi bawah air (AUV) mempunyai potensi yang besar untuk menyelam jauh di bawah laut dan melakukan pelbagai operasi. Tetapi, AUV beroperasi dengan jumlah kapasiti bateri yang terhad. Untuk mengatasi masalah ini, dok di bawah air adalah perlu supaya apabila AUV melakukan dok, ia dapat mengecas baterinya kembali sehingga kapasitinya penuh. Salah satu cara untuk melakukan dok bawah air adalah melalui pengawalan robot berdasarkan penglihatan atau penglihatan servo. Terdapat banyak kaedah untuk melakukan penglihatan servo seperti penglihatan servo berasaskan kedudukan (PBVS), penglihatan servo berasaskan imej (IBVS), dan penglihatan servo 2-½-D. Walau bagaimanapun, kaedah-kaedah ini gagal apabila tiada kesamaan ciri-ciri sasaran antara imej yang diperolehi dan yang dikehendaki. Masalah ini timbul apabila ciri-ciri sasaran daripada imej yang diperolehi berada di luar had imej atau disebabkan kedudukan AUV yang miring atau ciri-cirinya kelihatan rosak akibat keadaan bawah air yang tidak menentu. Untuk menyelesaikan masalah ini, kaedah keboleh-tukaran rujukan IBVS dicadangkan dalam kajian ini. Untuk merealisasikan kaedah yang dicadangkan, sistem kawalan berdasarkan Kadaran-Kamiran dan Gelangsar-Cara dibangunkan untuk mengawal pergerakan AUV. Kemudian, sistem penglihatan dibangunkan berdasarkan pembelajaran mendalam untuk mengesan dan mengklasifikasikan sasaran yang dipasang di stesen dok. Susulan itu, kaedah keboleh-tukaran rujukan IBVS dibangunkan untuk

membimbing AUV ke dalam stesen dok. Konsep asas kaedah yang dicadangkan adalah untuk melaksanakan penukaran yang diperlukan pada ciri-ciri sasaran yang dikehendaki untuk menyamai ciri-ciri sasaran yang sedang diperolehi. Kaedah ini juga membolehkan AUV untuk bertukar antara dua mod operasi iaitu balik dan dok. Selain itu, prototaip AUV dan stesen dok telah dibangunkan untuk mengesahkan keputusan simulasi. Secara simulasi, sistem kawalan yang telah dibangunkan mempunyai tindak balas untuk mengikut trajektori yang dikehendaki sebanyak 93.89% dan lasak menghadapi arus air dari sisi sehingga 0.1 meter sesaat. Bagi sistem penglihatan yang dibangunkan pula, ketepatan pengesanan dan klasifikasi sasaran berdasarkan daripada matriks kekeliruan adalah 96.68% dan 99.72% masing-masing. Kemudian, untuk keboleh-tukaran rujukan IBVS, apabila dinilai, kaedah yang dicadangkan cemerlang dalam kebolehpercayaan untuk mengelak perlanggaran antara AUV dan stesen dok iaitu 83.33% dan lebih lasak dalam menghadapi masalah ciri-ciri sasaran yang hilang jika dibandingkan dengan kaedah IBVS yang biasa dan kaedah IBVS dengan pengawalan tetap sebanyak 100%. Akhir sekali, hasil daripada eksperimen, bilangan percubaan yang berjaya bagi dok bawah air menggunakan kaedah yang dicadangkan adalah 20 daripada 24 atau 83.33%.

SWITCHING REFERENCE IMAGE-BASED VISUAL SERVOING FOR UNDERWATER DOCKING OF AUTONOMOUS UNDERWATER VEHICLE

ABSTRACT

Autonomous underwater vehicle (AUV) has great potential to dive deep under the ocean and perform various tasks. However, the AUV operates on a limited amount of battery capacity. To overcome this limitation, underwater docking is required so that when the AUV docks, it is able to recharge the battery to full capacity. One of the ways to achieve underwater docking is by means of vision-based robot control or visual servoing. There are many methods to perform visual servoing such as position-based visual servoing (PBVS), image-based visual servoing (IBVS), and 2-½-D visual servoing. Nevertheless, these methods failed when there is no resemblance of target features between acquired and desired images. Such problem arises when the target features from acquired image could be out of image plane or disoriented due to AUV's skewed position or appeared to be disfigured due to harsh underwater conditions. To resolve this problem, a switching reference IBVS method is proposed in this study. To realize the proposed method, a control system based on Proportional-Integral and Sliding-Mode controllers are developed to control the AUV movement. Then, vision system is developed based on deep learning to detect and classify targets installed on the docking station. Subsequently, the switching reference IBVS method is developed for guiding the AUV into the docking station. The underlying concept of the proposed method is to switch the desired target features to match the currently acquired target features. The method also enables the AUV to switch between two modes of operation which are homing and docking. In addition, an AUV and a docking station prototypes have been developed to verify simulation results. Simulation wise, the developed control system has responsiveness to track desired trajectory by 93.89% and robust under the effect of lateral water current up to 0.1 meter per second. As for the developed vision system, the detection and classification accuracies of targets based on confusion matrix are 96.68% and 99.72% respectively. Then, for switching reference IBVS, when benchmarked, the proposed method excelled in reliability to avoid collision between AUV and docking station by 83.33% and more robust under the effect of missing target features when compared to normal IBVS method and IBVS with attitude keeping control method by 100%. Finally, from experimental result, the number of successful trials for underwater docking using the proposed method is 20 out of 24 or 83.33%.

CHAPTER ONE

INTRODUCTION

1.1 Background and Motivation

On the ocean surface, man can swim as far as the eyes can see, but under the ocean, man cannot dive down for more than 40 meters as the deeper the ocean is, the greater the pressure will be. For centuries, the underwater world remains to be a very mysterious place. Due to this, rapid advancement of autonomous underwater vehicle (AUV) has taken place. An AUV is an underwater robot which travels to the bottom of the ocean without being controlled by an operator. It has been used to perform the mapping of seafloor, finding airplane wreckages, collecting oceanographic data, inspecting underwater pipeline, and closely checking on the bottom part of a ship (Wynn et al., 2014). Figure 1.1 shows various types of AUV developed by Bluefin Robotics performing different kinds of underwater operations.

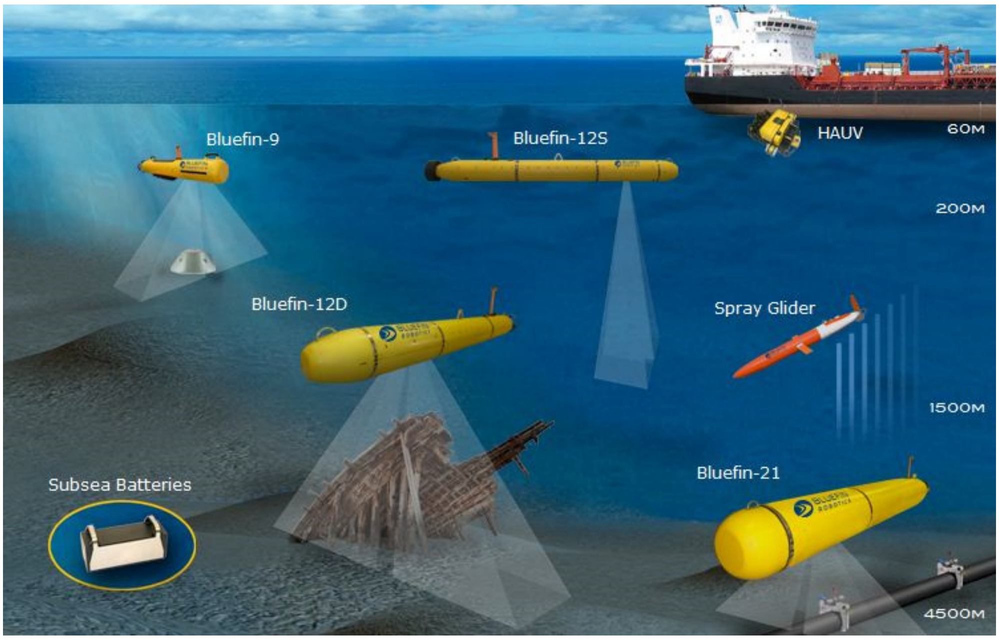

Figure 1.1: Various AUVs developed by Bluefin Robotics to perform various tasks (Francis, 2016)

Although the possibilities of using AUV for underwater applications are limitless, current challenges of the technology still has much to ponder. For example, it has slow propulsion speed, low-resolution sensory system, and cannot perform sophisticated operations. All of these happened in order to compensate and conserve the limited amount of power embedded into the system. Moreover, it is just not feasible to continuously deploy and retrieve low-powered AUV on a day-to-day basis to recharge the battery. As an alternative, a solar-powered AUV (SAUV) was made to harness the energy from the sunlight. But on the contrary, the design of the AUV had to be modified which affect its maneuverability while at the same time the recharging rate is not quick enough. At best, SAUV requires two days to fully recharge a battery starting with 20% in reserve (Crimmins et al., 2005). A better solution is to deploy an underwater docking station where the AUV can recharge its battery (McEwen et al., 2008). Figure 1.2 shows an imaginative underwater docking operation.

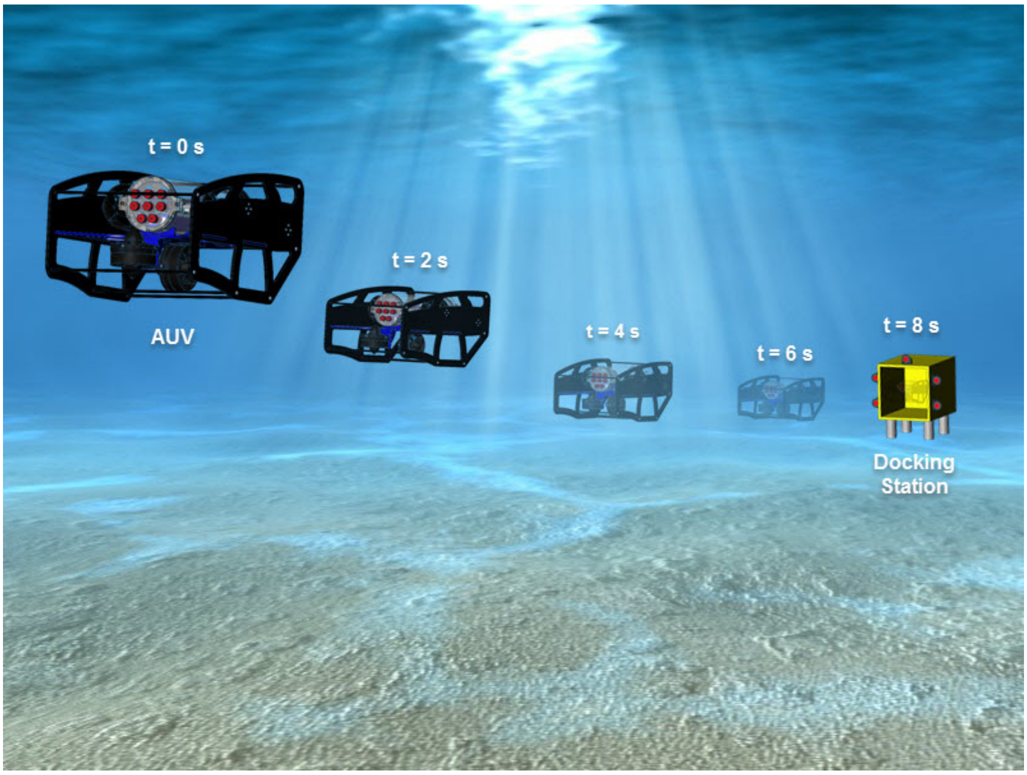

Figure 1.2: Imaginative underwater docking of an AUV

Apart from battery recharging, docking allows uploading of collected data and downloading of mission operations. Examples of data collections are about acoustic study of marine life, side-scan sonar image of shipwreck at the bottom of the sea, and research on hydrothermal vents. Then, examples of mission operations are underwater mine counter-measures, port and harbor security, and ship hull and infrastructure inspection. Additionally, a docking station makes the process of Launch and Recovery System (LARS) of an AUV much easier. As some of the AUVs can weigh up to a few tons, by securing the AUV to dock inside a docking station first, makes the job of lifting it more efficient.

Currently, AUV uses acoustic or sense of hearing in many underwater fields such as for communication and localization. However, docking of AUV by means of acoustic is only suitable when the distance is far. As the AUV gets closer to the station, acoustic will no longer be valid due to multi-path echoing of sound and the sound varying propagation delays. Instead, optical or sense of sight has much to offer in any short distance related task. The sight can act as a source of guidance for the AUV to dock into the station. When the AUV is guided by vision, this is known as vision-based robot control or visual servoing. Basically, visual servoing relies on two completely different fields of study consisting of computer vision and control system. When both of the fields are combined together, this brings great advantages to any robot. Among the advantages are sensing of the environment, improving the robot versatility, and significant increase in the robot accuracy. Table 1.1 listed down description of each advantages.

Table 1.1: Advantages of visual servoing

Aspects	Description
sensing of environment	acquire valuable information from surrounding, especially certain object's characteristics such as color, shape, and texture
improve robot's application versatility	visual information is useful to add to the robot's capabilities as such it can performs mapping and inspection
increase robot's accuracy	vision information can be used as visual feedback to adjust robot's position and orientation more reliably

Perfecting visual servoing remains to be a very challenging task, particularly in dealing with its shortcomings. Among the major downsides of visual servoing are the requirement of a high-computing system, limited line of sight, and complex data interpretation. However, the visual servoing technique displays great potential for any robotics system which requires perception within its workspace such as in the case for close-range underwater docking of AUV. This perception characteristic makes the research on visual servoing highly valuable with specific purpose to overcome its drawbacks and utilize the benefits for useful applications in the future. Table 1.2 summarized the technical disadvantages of the visual servoing technique.

Table 1.2: Disadvantages of visual servoing

Aspects	Description
requires high-computing system	imagine 640 pixels wide times 480 pixels high or 307,200 amount of data needed to be processed in just a fraction of a second
limited line of sight	cone of vision of camera is less than 180 degrees and line of sight is viable for short distance
difficult data interpretation	image is in the form of 2-dimensional (2D) perspective projected from 3-dimensional (3D) world may cause loss of depth information

1.2 Problem Statement

The main purpose of AUV in real application is to work independently and continuously throughout the day. However, the AUV's operation can only last for so long until the on-board battery is exhausted. To recharge the battery autonomously, underwater docking is necessary. In order to perform underwater docking, the AUV needs to be guided by visual information when it gets near to the station. The two most commonly used approach to perform underwater docking using vision are single image-based guidance (Maki et al., 2013, Myint et al., 2016b) and single image-based coupled with attitude keeping control guidance (Park et al., 2009, Li et al., 2015c). To implement these approaches are not easy. All things considered, one has to indulge in robot control, vision processing, and visual guidance just to make the docking process work. To add, there are many existing issues about underwater docking due to the dynamic nature of the underwater environment.

The first issue is in regards to the control of AUV. To control the AUV movements, proper modeling is crucial. However, the modeling will not be perfect as it is hard to determine the hydrodynamics effects acting on the AUV. In addition, the effects are nonlinear. Since the effects of hydrodynamics are nonlinear, the designed robot controller had to be of nonlinear type. There are several nonlinear controllers used on AUV such as state feedback linearization (Cao and Su, 2011), integrator backstepping control (Rath et al., 2017), and sliding-mode control (Elmokadem et al., 2016). However, for sliding mode control in particular, it is difficult to determine the optimal controller design parameters. It is also difficult to control the AUV if it is an under-actuated system. Coupled this with current image-based guidance system, there are few times collision would occur between the under-actuated AUV and the docking station (Jin-Yeong et al., 2007).

The second issue is in regards to using vision system to extract features of target from a docking station. Using vision in underwater is a very challenging task as the underwater scenery changes frequently. The changes are in terms of turbidity, light reflection, illumination, mirrored target under the surface of the water, and appearance of suspended particles. When encountered with one of these problems, it distorts how the target looks like. Apart from these challenges, another challenge is on the usage of light as a target for docking. When multiple similar light targets are used, there is the issue of determining the order of each target and this creates confusion. When confusion happened, the vision system would be unable to track the target properly.

The third issue for underwater docking is in regards to the visual servo control of AUV. There are many visual servo control methods used for underwater docking of AUV. Some of the methods are position-based visual servoing (Heshmati-Alamdari et al., 2014a), image-based visual servoing (Gao et al., 2016b), hybrid visual servoing (Cesar, 2017), and multi-camera visual servoing (Myint et al., 2015). However, all of these methods have one major fallacy. It was stated that visual servo system would fail if features of the acquired target are different from the desired target (Jin-Yeong et al., 2011). Furthermore, when the AUV is at a skewed position relative to the station, acquired target would be disoriented and docking would be unsuccessful. Therefore, the problem statement of this research is:

Current visual servoing methods for underwater docking of AUV failed when there is no resemblance of target features between acquired and desired images. Such problem arises when the target features from acquired image could be out of image plane or disoriented due to AUV's skewed position or appeared to be disfigured due to harsh underwater conditions.

1.3 Research Objectives

The aim of this research is to seek knowledge and introduce new ideas about robust visual servoing system focusing on solving the major issue in which underwater docking of an AUV failed due to no resemblance between desired and acquired target features. To realize this aim, the objectives are:

1. To design and develop a responsive motion control system for an AUV.
2. To develop a robust object tracker for detecting and classifying targets placed at a docking station.
3. To develop a new visual servoing system for guiding the AUV into the docking station.

1.4 Research Scopes

The scopes of this research are listed as follow:

1. In the aspect of control system, the underwater vehicle can independently control at least three degrees of freedom (DOF) so that it has sufficient maneuverability to operate in 3D underwater environment. In addition, the effects of hydrodynamics are minimized such as only lateral current is considered for robustness analysis, the AUV is symmetry about all axes, and neglecting certain terms when the AUV operate at speed less than 2 m/s.
2. Regarding vision system, the underwater vehicle has only forward-looking camera to minimize algorithm complexity and power consumption. Additionally, the initial image captured from a camera should have some information about the docking station. With this, the robot can be guided based from the extracted features of the target placed at the docking station.

3. For the setup of visual servoing process, the initial distance separating the robot and the docking station is at least 5 meters. If too close, the AUV does not have enough space to maneuver or docking would become too simple depending on how the robot is positioned. Whereas, if too far, the vision processor might not be able to extract valuable information from the docking station and thus there is no guidance available for the robot.
4. In the aspect of prototype development, the robot has tethered cables attached to it so that it is easier to monitor real-time data. Despite the tethered cables, the underwater vehicle performs its duty autonomously as such any AUV should be.
5. For test environment, it is going to be conducted in diving pool instead of the ocean as it is easier to manage logistically and to minimize expenditure. So, the water has low turbidity and only has shallow water disturbances such as light reflections, brightness change, and low number of suspended particles. Furthermore, the focus of the research is more onto proving the concept as main aim rather than implement it in the sea which could take considerable amount of time and effort and dealing with other unexpected circumstances.
6. In regards to application aspect, this research tackles docking application, therefore, the other task usually associated with docking such as charging of battery, undocking, or launching and recovery for example, are not going to be performed.

1.5 Thesis Outline

This thesis consists of five chapters and brief descriptions of each chapter are described as follow: Chapter 1 describes motivation about this study and background knowledge about underwater docking of AUV using visual servoing in general. Problem statements, research objectives and research scopes are also conversed. In Chapter 2, literature review on underwater docking of AUV is discussed in detail. The latest works related to the control of AUV, object detection and recognition methods, visual servoing methods, and docking of AUV techniques are explored to find knowledge gaps. Then, suitable methods are selected as a way forward in tackling problems related to underwater docking of AUV. In Chapter 3, methodology or how the research is conducted is explained in detail. The methodology covers the theoretical as well as implementation aspects for control system, vision system, visual servoing, and prototypes development. Then, Chapter 4 is dedicated to results and discussions from conducted simulation and experimentation. Performance metrics are introduced as measuring indicator to find how good or bad the result is. In addition, benchmarks are made to compare the proposed method with existing methods. Finally, Chapter 5 highlights the research findings, contributions made and suggestions for improvements for future works.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

Underwater docking of an AUV using vision is an exciting research study yet challenging in the field of robotics. There are a lot of issues regarding underwater docking which have drawn much attention over the last two decades. Focus of this research involves multiple disciplines which can be difficult to take if not outline in a careful order. Therefore, it is important to firstly explain about how the literature review is conducted.

In this research, the literature review is conducted based on four steps. The first step is to get an overview of the research field and to list down some common and recent methods. Then, the second step is to study those methods thoroughly. Next, the third step is to make comparison of the methods. Finally, the fourth step is to find the knowledge gaps based on the comparisons made. The knowledge gaps are problematic issues faced by researches that are not yet solved.

2.2 Overview of Research Field

The research field consist of two parts: general and specific. The general part of research conveys common information about robotics. In robotics, there are three matters to consider which are application, technology, and fundamental. To describe, the application of this research is about docking, the technology revolves around underwater robotics specifically hovering AUV, and the fundamental focuses on vision-based. Figure 2.1 shows the general part of research interest.

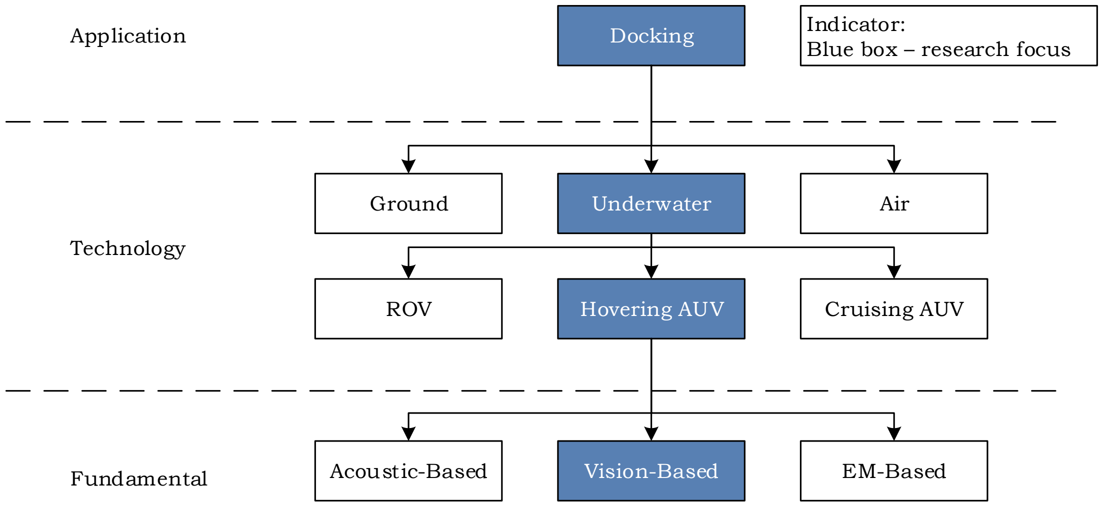

Figure 2.1: General part of research interest

Focusing on the technology part of Figure 2.1, there are three types of underwater vehicles: ROV, hovering AUV and cruising AUV. ROV stands for remotely operated vehicle. This type of underwater vehicle is manually controlled by an operator through a tethered cable. Then, hovering AUV is an underwater vehicle usually has box-shaped body and has at least three DOFs actuation. Lastly, cruising AUV is an underwater vehicle of torpedo-shaped body and usually has at most two DOFs actuation. The cruising AUV can last for a very long time compared to hovering AUV. Since hovering AUV has short operating time and requires frequent recharging, the focus of underwater docking is on this type of robot.

Also, from Figure 2.1, a more detailed review is to be conducted on the fundamental level. The fundamental level is basically the specific part of the research interest. Instead of the acoustic-based or electromagnetic-based, the research interest is on vision-based robot control also known as visual servoing. There are four sections that contributes to the development of a visual servoing system for underwater docking of AUV. The first three sections are robot control, vision system, and vision control (Corke, 2011) and another section is underwater docking algorithm.

As mentioned, the first section is about robot control. Generally, there are two types of robot control methods: linear and non-linear. For linear control methods, the focus of literature is on the proportional-integral-derivative (PID) and linear-quadratic regulator. As for non-linear control methods, survey is conducted on state-feedback linearization, integrator backstepping, and sliding-mode control.

Then, the second section is to gain knowledge about vision system. Although what makes up a vision system consist of image acquisition and image pre-processing, the priority of literature is given to object detection and recognition. The common methods for object detection and recognition are image segmentation and blob analysis, template matching, feature extraction and learning model, bag-of-words model, and deep learning model which are going to be reviewed accordingly.

Then, the third section is to study works related to vision control. There are two taxonomies or classifications of vision control. They are end-point closed-loop and end-point opened-loop. Basically, the end-point closed-loop means the camera is attached to the body of the robot and so the camera can give feedback in a closed-loop manner. Oppositely, the end-point opened-loop means the camera is not attached to the body of the robot and it just stays static continuously observing the target and robot therefore opened-loop. The focus is on the end-point closed-loop vision control. Then, there are two basic methods for end-point closed-loop vision control: position-based visual servoing and image-based visual servoing. Other methods included in review are 2-½-D visual servoing and multi-camera visual servoing.

Lastly, the fourth section of literature review is about underwater docking algorithms. Most underwater docking algorithms for AUV uses either single image-based approach or a combination of single image-based with attitude keeping control approach. Figure 2.2 illustrates the specific part of literature review.

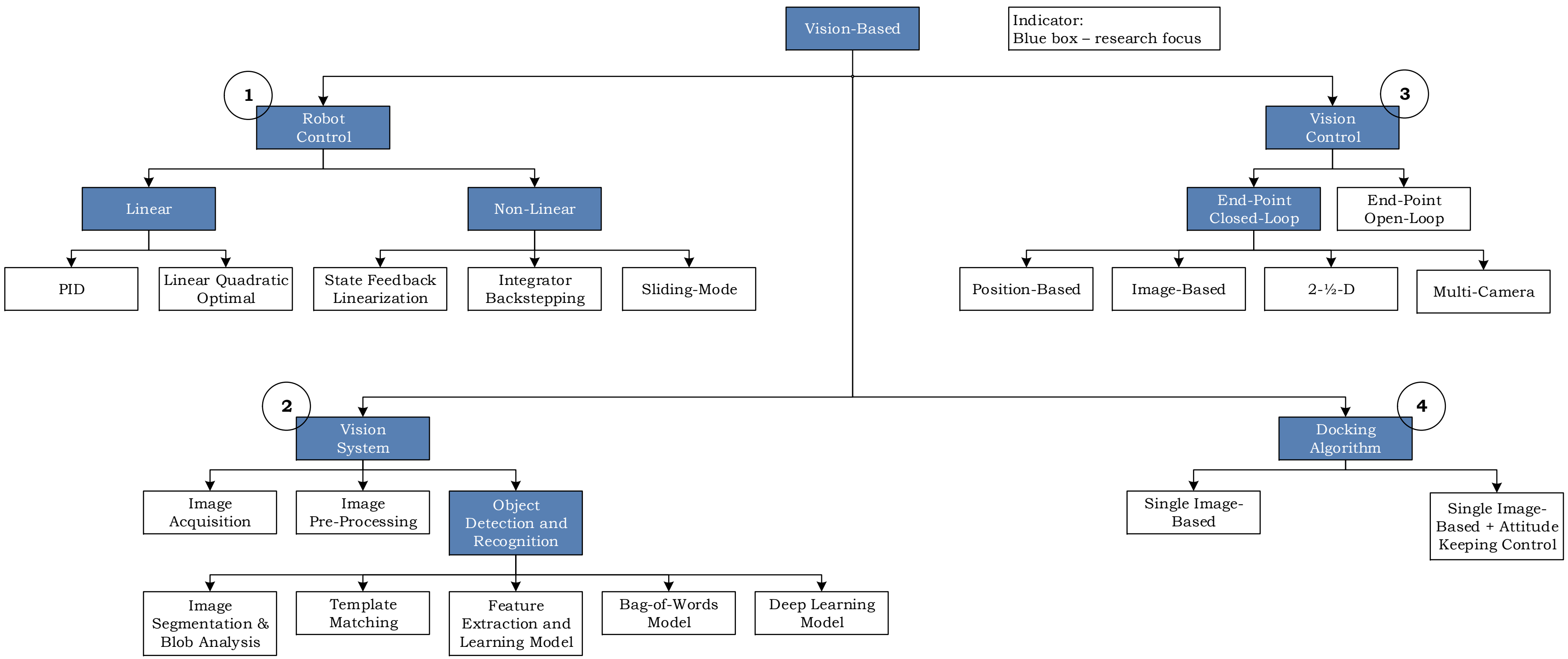

Figure 2.2: Specific part of research interest

2.3 AUV Motion Control Methods

Every mobile robotic system requires some sort of a motion control to have some degrees of desirable result when moving from one point to another point. Before studying the various kind of control methods, understanding the basic concept of a control system is of importance. The basic flow of a control system is to have an input, a controller, a robot system, and an output. There are two basic classes of control systems: open loop and closed loop. To compare, open loop control system is easy to design and economical, but with no feedback and therefore inaccurate. On the other hand, closed loop control system is difficult to design and not economical, but with feedback and therefore accurate. The closed loop control system is selected to get accurate AUV movement. Figure 2.3 shows a basic block diagram of a closed loop control system.

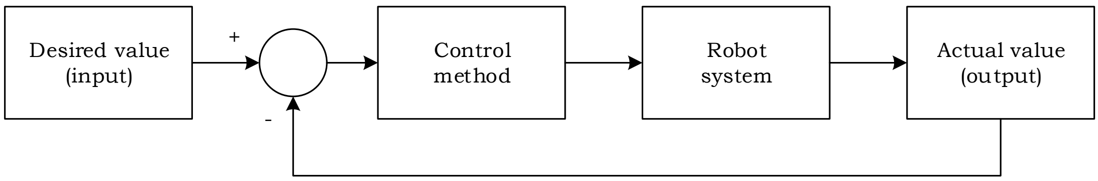

Figure 2.3: Basic block diagram of a closed loop control system

For this research, one of the main focus is on controlling the AUV's motion using suitable closed loop control methods for underwater docking. There are a lot of control methods had been proposed and used on AUV over the years. More emphasis is given to popular control methods such as proportional-integral-derivative, linear quadratic optimal, state feedback linearization, integrator backstepping, and sliding-mode control.

2.3.1 Proportional-Integral-Derivative Control

The proportional-integral-derivative or simply known as PID is the most widely used classical control method. It is of a linear type control system. By linear type, it means the control method is only able to control linear kind of system. A system is said to be linear when the equation which represents the system is of a polynomial of degree 1. The polynomial when plot on a graph always depicts a straight line and so it is called linear system. The basic principal of using PID is by tuning its proportional, integral, or derivative terms to achieve a desirable performance. The proportional term determines how far to get to the desired value. The integral term eliminates the steady state error between desired value and actual value. The derivative term determines how fast to get to the desired value. Depending on the performance criteria, a more efficient approach is to select only necessary terms in which PID might be reduced to either P-term, PI-term, or PD-term.

Among the recent research of utilizing PID to control the motion of AUV are genetic algorithm (GA) based PID (Qiang et al., 2009), fuzzy PID (Hu et al., 2013), and fully-actuated AUV PID control (Hammad et al., 2017). The GA based PID optimizes the terms for controlling the heading of an AUV, the fuzzy PID tune the terms based on inference or forming rules for depth control, and the fully-actuated AUV PID control focuses on speed control. Additionally, a research has been conducted for way-point tracking control of hovering AUV using multiple PID controllers (Kim et al., 2015). The multiple PID controllers are designed to control the vertical plane (depth and pitch) as well as the horizontal plane (surge, sway and heading). Figure 2.4 shows a block diagram of horizontal direction control for hovering AUV.

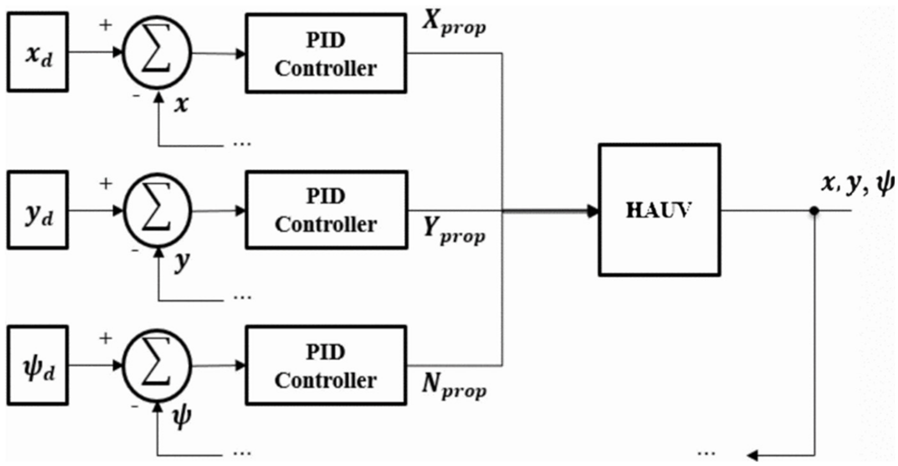

Figure 2.4: Horizontal direction controller (Kim et al., 2015)

In all, a PID control method has a simple concept. The concept is to tune the terms in the controller to achieve desired transient and steady-state response. In other words, implementing a PID controller is easy. However, to get an optimal performance by changing the terms' values is difficult. Also, it has low robustness to disturbances and ignores the behavioral change of the system.

2.3.2 Linear Quadratic Optimal Control

Linear quadratic optimal control is another type of linear controller. It is based on developing a control law for a system in such a way that the optimality standards are achieved. The underlying principal is known as linear quadratic regulator (LQR) (Fossen, 2011). The word linear refers to it accepts a linear type of system, quadratic is the cost function based on the integral of a quadratic form to be minimized, and regulator describes the goal of the controller to bring output of the system to zero or a constant value. If a system is nonlinear, the system has to be linearized at certain operating point so that the controller could be used. However, the system also has to be checked for controllability (any input is acceptable to control a state) and observability (any state can be observed) for control implementation.

One of the most recent research of using LQR is on the control of underwater glider (Tchilian et al., 2017). In the research, LQR is used to track a reference for the underwater glider to follow. Since the glider only has a single propeller mounted at the back and two wings attached to the left and right side of its body, the tracking trajectory is of zig-zag motion. Other researches of using LQR are on the depth control of a fully-actuated AUV (Reshmi and Priya, 2016) and under-actuated AUV (Gao et al., 2016a). As hydrodynamics causes the AUV equation of motions to be nonlinear, they are reduced and linearized to a diving subsystem model for LQR implementation. The later work was extended by analyzing the performance of the proposed controller when taking into consideration a disturbance of irregular wave forces acting on the AUV (Yang et al., 2016). Additionally, a comparison study between LQR and fuzzy logic control has been conducted where LQR shows smoother steering of an AUV (Rundqvist, 2005).

To summarize LQR control method steps, firstly, the system has to be a linear system, secondly is to make sure the system is controllable and observable, thirdly is to develop quadratic cost functions, and fourthly is to regulate the error to zero while minimizing the cost function. It is expected that the response obtained to be optimum for linear system depending on the cost function. However, as LQR and PID control methods are only suitable for linear system, problem might arise when the system experiences some unexpected disturbances. This can cause the normal operating point to produce a performance that might no longer be valid. To overcome this issue, nonlinear types of controllers are more preferable to control a system with nonlinearities.

2.3.3 State Feedback Linearization Control

State feedback linearization control is a method to perform control by changing a nonlinear system into an equivalent linear system. The linearization of the nonlinear system consists of three basic steps (Nise, 2015). The first step is to use state space representation to kind of organize all of the different states in the system. Then, the second step is to linearize each states to find an equilibrium point. The equilibrium point is a constant solution to differential equation that makes a system linear. Finally, the third step is to form an overall linearized state space model. When the system is linear, a linear controller such as PID or LQR could be designed and implemented. The linear controller will be fed by multiple linearize states of the system and produces a control output that makes the plant controllable. Figure 2.5 shows the conversion of nonlinear system to a linear system by means of state feedback linearization.

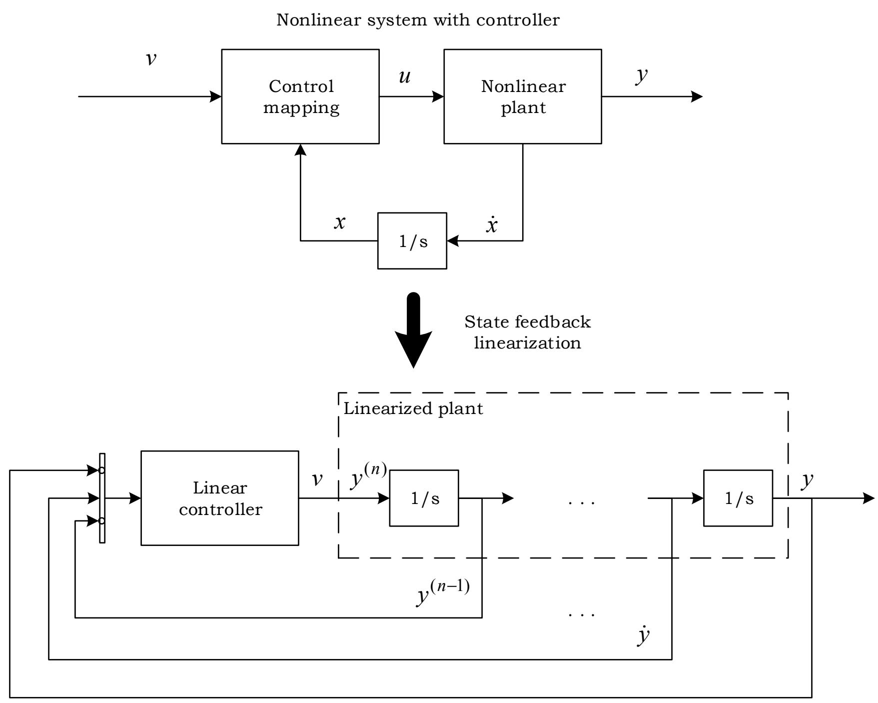

Figure 2.5: Conversion of nonlinear system to linear system using state feedback linearization (Khalil, 2002)

The state feedback linearization control method has been used to control AUV in several studies. In one study, it produces more accurate, robust and stable heading control when compared to Taylor linearization technique (Cheng et al., 2008). The stated reason was that Taylor linearization ignored the nonlinearity and uncertainties terms altogether when the state feedback is not. The state feedback aimed at canceling those terms when the system equations are arranged into a controllability canonical (simplest) form. In another study, the controller is used to control the surge, heave, and yaw of an under-actuated hovering AUV (Vervoort, 2008). The under-actuated hovering AUV have six thrusters for propulsion. Then, apart from the hovering AUV, the controller has also been used to control the diving plane specifically the depth and pitch (Cao and Su, 2011) and for roll stabilization (Pan et al., 2011) of cruising AUVs.

In all, the advantage of using this method is in terms of its applicability to any nonlinear system. Also, when the nonlinear system is linearized, any kind of linear controllers could be designed to control the system. In other words, this method allows the usage of linear controller onto a nonlinear system when in most cases it is not appropriate. Although this method bridged the gap between linear controller and nonlinear system, one of the disadvantages is the inclusion of zero dynamics that may be unstable (Fossen, 2011). Specifically, using state feedback linearization, there are certain system state that is not observable and the zero dynamics may make this state to go to zero. Apart from the not observable state problem, cancelling all the nonlinear terms causes the linearized system to be very sensitive to errors. This would make the performance of the system to degrade over time when the uncertain term such as ocean current starts to take effect on the system over prolonged duration.

2.3.4 Integrator Backstepping Control

Integrator backstepping control is also known as feedback-stabilizing control method. It is quite similar to state feedback linearization control. According to Fossen (2011), the integrator backstepping control has six steps. The first step is to determine design objectives. For example, a design objective can be regulating an output x_1 to zero as time goes to infinity. The second step is to specify a virtual control input x_2 based on the design objectives to get new backstepping state variables z_2. The third step is about design of stabilizing function α_1 which will provide necessary feedback for the backstepping variables. The fourth step is to perform dynamics computation by time differentiation of z_2 based on the stabilizing functions. The fifth step is to combine the backstepping equations into a canonical form. The sixth or final step is to investigate the stability of the canonical form using Lyapunov function. Figure 2.6 shows a block diagram of a basic integrator backstepping when all of the aforementioned steps are applied.

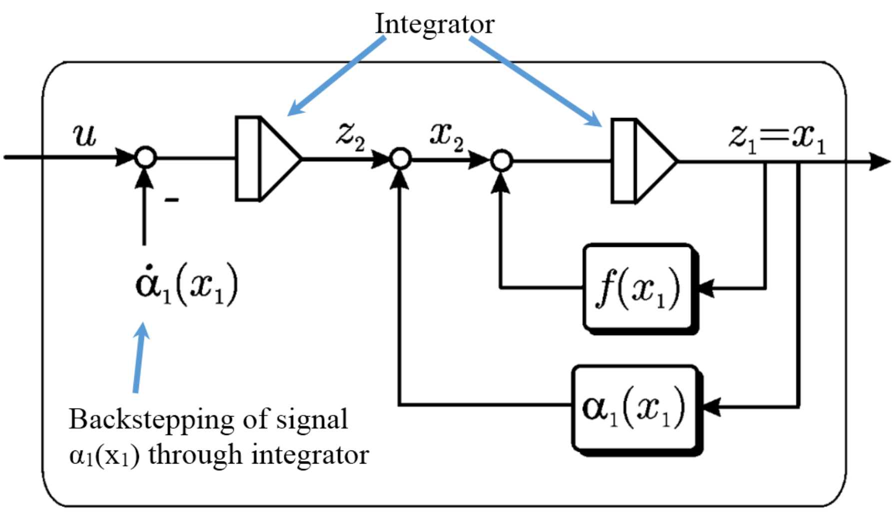

Figure 2.6: Basic integrator backstepping block diagram (Fossen, 2011)

There are few researches that utilizes integrator backstepping to control an AUV. In one study, the integrator backstepping is used to control an under-actuated AUV called X4-AUV (Zain and Harun, 2016). The control is applied to translational subsystem as well as rotational subsystem of the AUV. Apart from that, the controller was used for tracking control of a three DOF AUV focusing on the diving and steering plane (Rath et al., 2017). Then, another study is about docking application where a backstepping adaptive control was proposed on fully actuated AUV (Gao et al., 2014). The AUV uses Ultra-Short Baseline (USBL) for underwater positioning and the controller is used to correct the positioning. Additionally, the controller has also been used with Robust Exact Differentiator (RED) in trajectory tracking (Cervantes et al., 2016). The RED basically generates velocity information to be fed to the controller and the result produced is much better than just using the integrator backstepping.

To summarize, the integrator backstepping is quite similar to state feedback linearization with noticeable difference is that it handles nonlinear terms. The "good nonlinearity" terms are handled directly while the "bad nonlinearity" terms are handled by adding nonlinear damping to compensate. Example of "good nonlinearity" is an absolute value of a state variable and example of "bad nonlinearity" is quadratic of a state variable. Adding nonlinear damping ensures that the controller is less sensitive to modeling error. Therefore, the controller has more flexibility and more robust than state feedback linearization. However, the controller has two things to consider to produce a desirable result. The first thing is that it is important to avoid expression involving time derivatives of the states to avoid design control complexity. The second thing is that the state equation has to be analyzed in classifying what is considered as "good" or "bad" nonlinear terms and how to handle them properly.

2.3.5 Sliding-Mode Control

A sliding-mode control (SMC) is a robust nonlinear controller with the ability to handle model uncertainty. The controller objective is to make a sliding variable goes to zero as time approaches infinity. The sliding variable is defined as the tracking error times eigenvector of a closed loop system. The word "eigen" means characteristic. An SMC requires four basic steps (Fossen, 2011). The first step is to place desired poles to a closed loop system. Then, in the second step, the eigenvector is decomposed from the desired closed loop system. Next, in the third step, a sliding variable is computed. Finally, in the fourth step, the tracking controller is calculated. The first and second steps concern about getting normal feedback term while the third and fourth steps are about getting switching term. The difference between the two terms are the normal feedback term is for obtaining desired closed loop dynamics while the switching term is for handling model uncertainty.

SMC had been used on AUV for depth control (Siang and Arshad, 2015), yaw control (Medina et al., 2016, Akçakaya et al., 2009), tracking control under ocean currents (Farhan et al., 2017), and tracking control for under-actuated system (Elmokadem et al., 2016). Apart from its normal usage, there are several improvements made to the SMC for controlling an AUV. In one study, the switching term of SMC was tuned using extreme learning machine (ELM) (Wang et al., 2017). Also, in the study, two control loops were designed consisting an outer and an inner control loops. The outer control loop is to control depth by means of proportional controller and the inner control loop is to control pitch based on SMC as depicted from Figure 2.7.

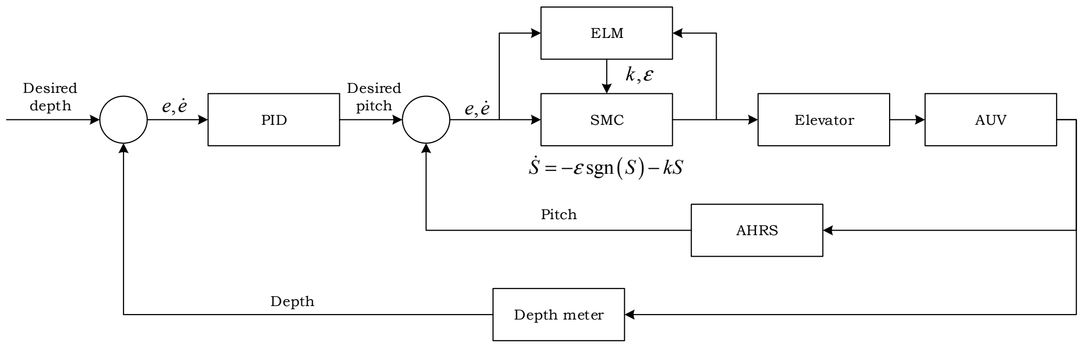

Figure 2.7: Two control loops for diving subsystem (Wang et al., 2017)

In another study, a combination of method consisting of backstepping and SMC are used to control an autonomous underwater glider (Mat-Noh et al., 2017). Apart from the autonomous underwater glider, this combination of method has been used on an AUV with a neural network added to the system to tune SMC switching term (Chu and Zhu, 2015). Basically, higher switching term gain adds robustness to the controller at the cost of performance while lower switching term gain make the controller performs better but lacks robustness to handle any disturbance. The study considers a minimum disturbance acting on the system. Additionally, instead of the basic SMC, higher order SMC had been used on AUV in various studies such as for neutralizing uncertainties and disturbances (Abolvafaie et al., 2016), in regards to dynamic region concept (Ismail and Putranti, 2015), and for diving plane control (Ruiz-Duarte and Loukianov, 2015).

As a conclusion, SMC has a simple design principle yet very robust to handle model uncertainties and unexpected disturbances. On the other hand, there are some issues such as finding suitable desired poles for closed-loop system and configuring the tuning parameter of switching term gain to get the perfect balance between performance and robustness.

2.3.6 Controller Comparisons

All of the reviewed control methods can be compared based on five aspects: system compatibility, design complexity, optimal configuration, flexibility, and robustness. System compatibility is to state what kind of system is applicable for the controller to works with without problem. Design complexity is based on the number and difficulty of steps taken to implement the controller. Optimal configuration is for setting up the controller to give best performance (minimum tracking error). Flexibility is to describe the controllers' adaptability to new conditions or situations. Robustness is the ability of the controller to give acceptable result under the influence of model uncertainty and disturbances. Table 2.1 listed the comparison of control methods based on conducted review.

Table 2.1: Comparison of control methods

Control methods	**Comparison aspects**				
	System compatibility	**Design complexity**	**Optimal configuration**	**Flexibility**	**Robustness**
PID	Linear	Very low	Hard	Very low	Very low
Linear quadratic optimal	Linear	Low	Easy	Low	Low
State feedback linearization	Nonlinear	Medium	Hard	Medium	Medium
Integrator backstepping	Nonlinear	Very high	Easy	Very high	High
Sliding-mode	Nonlinear	High	Hard	High	Very high