OBSTACLES MAPPING BASED ON 3-D PERCEPTION
FOR MOBILE ROBOT NAVIGATION

MS HENDRIYAWAN ACHMAD

DOCTOR OF PHILOSOPHY

UNIVERSITI MALAYSIA PAHANG

OBSTACLES MAPPING BASED ON 3-D PERCEPTION FOR MOBILE ROBOT NAVIGATION

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SUPERVISOR'S DECLARATION

We hereby declare that We have checked this thesis and in our opinion, this thesis is adequate in terms of scope and quality for the award of the degree of Doctor of Philosophy (Electronics Engineering).

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I hereby declare that the work in this thesis is based on my original work except for quotations and citation which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at Universiti Malaysia Pahang or any other institutions.

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ABSTRAK

Banyak penyelidik terdahulu telah menawarkan pemetaan dua dimensi untuk navigasi robotik. Walau bagaimanapun, kerana pemetaan dua dimensi hanya dapat mengesan halangan di bidang satah, penyelidik mencari cara lain yang lebih baik untuk mengetahui halangan di kawasan sfera. Kelemahan pemetaan dua dimensi untuk navigasi robot adalah bahawa ia tidak dapat mengesan halangan yang mempunyai perbezaan ketinggian. Penyelidikan ini menawarkan beberapa tahap untuk membina peta tiga dimensi. Tahap pertama adalah mengembangkan robot bergerak sebagai platform ujian. Robot memproyeksikan halangan dengan mengukur jarak menggunakan kamera kedalaman untuk mendapatkan maklumat geometri rintangan dalam bentuk titik klausa yang menunjukkan kedudukan mercu tanda pada koordinat X, Y, dan Z. Tahap kedua menawarkan kaedah menganggarkan peralihan dan putaran robot dengan tepat menggunakan teknik peleburan sensor, yang merupakan gabungan odometri roda, odometri visual, dan odometri inersia. Odometri roda menganggarkan kedudukan robot berdasarkan maklumat mengenai kelajuan putaran roda tanpa dipengaruhi oleh kehadiran cahaya, magnet, atau vektor graviti, tetapi odometri roda mempunyai masalah pengumpulan ralat. Odometri visual melakukan fungsi anggaran berdasarkan gambar visual dengan gabungan kaedah Features from Accelerated Segment Test (FAST) dan singular value decomposition (SVD). Walau bagaimanapun, odometri visual sangat bergantung pada kehadiran cahaya dan tekstur objek, semakin sedikit cahaya dan tekstur objek, semakin tinggi kesalahan estimasi kedudukan. Odometri inersia menggunakan pengukuran Magnetic-Angular-Gravity (MARG) kemudian menggabungkan ketiga-tiga pengukuran melalui kaedah Madgwick untuk menghasilkan nilai anggaran kedudukan yang tepat. Walau bagaimanapun, odometri inersia hanya dapat mengira pergerakan putaran. Kajian ini menawarkan kaedah peleburan berdasarkan Extended Kalman Filter (EKF) untuk menghasilkan output anggaran baru yang menghilangkan kelemahan setiap hasil anggaran (wheel odometry, visual odometry, inertial odometry). Tahap ketiga adalah pembinaan semula peta tiga dimensi berdasarkan anggaran kedudukan robot dan pengukuran kedalaman. Semua masalah ini dikaji dan diselidiki dari perspektif teori-teori melalui analisis matematik. Hasil yang diperoleh disahkan melalui penyelidikan eksperimen. Hasil ujian estimasi kedudukan menggunakan teknik peleburan multi-sensor berdasarkan kaedah EKF selama 120 saat di kawasan 10m x 10m menunjukkan nilai purata ralat peralihan paksi X 7.6cm, ralat peralihan paksi Y 8.5cm, ralat putaran roll 0.678°, ralat putaran pitch 0.491°, dan ralat putaran yaw adalah 0.483°. Hasil visual menunjukkan peta 3-D yang berjaya disusun semula mempunyai keretakan atau tumpang tindih minimum, dan mewakili situasi yang sama dengan kenyataan.

ABSTRACT

Many previous researchers have offered two-dimensional mapping for robotic navigation. However, since two-dimensional mapping is only able to detect the barriers in planar fields, researchers are looking for other better ways to discover the obstacles in the spherical area. The disadvantage of two-dimensional mapping for robot navigation is that it is unable to detect the barriers that have elevation differences. This research offers several steps in order to build a three-dimensional map. The first step is to develop the mobile robot as a test-bed platform. Robot projects the obstacles by measuring the distance uses depth camera to get obstacles geometry information in the form of point-cloud that show the position of landmarks on X, Y, and Z coordinate. The second step offers a method of estimating robot translation and rotation accurately using sensors fusion technique, which is a combination of wheel odometry, visual odometry, and inertial odometry. Wheel odometry estimates the position of the robot based on information on wheel rotation speed without being affected by the presence of light, magnetism, or gravity vectors, but wheel odometry has error accumulation issue. Visual odometry performs estimation functions based on visual images with the combination of Features from Accelerated Segment Test (FAST) and singular value decomposition (SVD) methods. However, visual odometry is very dependent on the presence of light and texture of the object, the less light and texture of the object, the higher the error of position estimation. Inertial odometry uses Magnetic-Angular-Gravity (MARG) measurement then combines the three measurements through the Madgwick method to produce accurate position estimation values. However, inertial odometry is only able to estimate rotational motion. This study offers a fusion method based on the Extended Kalman Filter (EKF) to produce a new estimation output that eliminates the weaknesses of each estimation result (wheel odometry, visual odometry, inertial odometry). The third step is the registration of three-dimensional map based on robot pose estimation and depth measurement. All these issues are examined and investigated from an estimation-theoretic perspective through mathematical analysis. The theories have been validated through experimental investigations. The results of position estimation test using multi-sensor fusion techniques based on the EKF method for 120 seconds in the area of 10m x 10m show the average value of X axis translation error of 7.6cm, Y axis translation error of 8.5cm, roll rotation error of 0.678°, pitch rotation error of 0.491°, and yaw rotation errors are 0.483°. The visual results show a 3-D map which successfully reconstructed has a minimal fracture or overlapping, and represent the same situation as the reality.

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LIST OF SYMBOLS

${}^{A}T_{B}$	homogenous transf. representing frame {B} with respect to frame {A}
${}^{A}\xi_{B}$	3-D relative pose frame {B} with respect to frame {A}
E	Euclidean distance
K	camera calibration matrix
M	map points
P	world points
R	orthogonal rotation matrix, $R \in SO(2)$ or $SO(3)$
t	translation matrix
T	homogenous transformation, $T \in SO(2)$ or $SO(3)$
u	eigen vector
v	linear velocity
$sin\,(\cdot)$	sine of
$cos\,(\cdot)$	cosine of
$f\,(\cdot)$	function of
$h\,(\cdot)$	function of
$SO(n)$	special orthogonal group, the set of all orientations in n dimensions
$SE(n)$	special Euclidean group (all poses) in n dimensions
$\mathbb{R}$	set of real numbers
$\mathbb{R}^2$	the space of all 2-D points
$\mathbb{R}^3$	the space of all 3-D points
X, Y, Z	cartesian coordinates
ϕ, θ, ψ	roll pitch yaw angles $\in SO(3)$
G_k	the Kalman gain
U_k	control signal
$P_{k\|k-1}$	current prediction error
S_k	the residual covariance
v_k	measurement noise
w_k	process noise
$X_{k\|k}$	state vector
$\hat{X}_{k\|k-1}$	current prediction state
$\tilde{Y}_k$	the measurement residual
$Z_{k\|k}$	observations vector
{F}	coordinate frame F
λ	eigen value
θ	robot heading
μ	mean

σ	standard deviation
σ^2	variance
ξ	abstract representation of 3-D cartesian pose
ω	angular velocity
$\in$	element of

LIST OF ABBREVIATIONS

1-D	one dimensional
2-D	two dimensional
3-D	three dimensional
AHRS	attitude heading & reference system
CMOS	complementary metal oxide semiconductor
COG	center of gravity
COTS	commercially of the shelf
DCM	direct cosine matrix
DMR	differential mobile robot
DO	depth odometry
DOF	degree of freedom
e.g.	example
EKF	extended Kalman filter
Eq.	equation
et al.	and others
Fig.	figure
i.e.	that is
ICP	iterative closest point
IMU	inertial measurement unit
LIDAR	light detection and ranging
LOAM	lidar odometry and mapping
LRF	laser range finder
MARG	magnetic angular rate gravity
MCU	microcontroller unit
MEMS	micro electro-mechanical system
PCA	principal component analysis
PID	proportional integral derivative
PWM	pulse width modulation
RANSAC	random sample consensus
RGB	red green blue
RGB-D	red green blue depth
RMSE	root mean square error
ROS	robot operating system
RTK-GPS	real time kinematic global positioning system
SAD	sum of absolute differences
SLAM	simultaneous localization and mapping
SVD	singular value decomposition
SVO	semi direct visual odometry
TOF	time of flight
TSDF	truncated signed distance function
VO	visual odometry
WO	wheel encoder

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