Review on Simultaneous Localization and Mapping (SLAM)

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***Abstract*— Simultaneous localization and mapping (SLAM) is a technique applied in artificial intelligence mobile robot for a self-exploration in numerous geographical environment. SLAM becomes fundamental research area in recent days as it promising solution in solving most of problems which related to the self-exploratory oriented artificial intelligence mobile robot field. For example, the capability to explore without any prior knowledge on environment it explores and without any human interference. The unique feature in SLAM is that the process of mapping and localization is done concurrently and recursively. Since SLAM introduction, many SLAM algorithms have been proposed to apply SLAM technique in real practice. The aim of this paper is to provide an insightful review on information background, recent development, feature, implementation and recent issue in SLAM.**

Keywords—Autonomous Mobile Robot, Extended Kalman Filter, Simultaneous Localization and Mapping, SLAM Algorithm and Technique

I. INTRODUCTION

In a past few decades, lots of research that focus on the autonomous navigation of mobile robots has been done. The objective is to find the best technique or solution to makes the robot capable to autonomously navigate without any prior knowledge on the environment it explores. In robotic field, autonomous robot becomes current most successful achievement as the robot itself able to perform tasks or behavior without human interference such as self-exploration. The objective of the robot is to self-explore on the unknown environment and avoiding the numerous landmarks and obstacles within the environment. For example like an exploration in grounded area such as terrain, subsea, aerial space and any places which possibly unreachable or potentially harmful to human can be done by the autonomous mobile robot.

The challenges face in self-exploratory oriented autonomous mobile robot is the environment factors which have numerous complex geographical landmarks and obstacles. Another challenges are capability of the mobile robot to explore and navigate without any knowledge on such unknown environment, generate its own map for the environment, able to recognize its own position, landmark and any obstacles, making decision based on the new environment data receive and able to navigate through the unknown environment without human interference.

Autonomous robot is a robot that capable to act and perform the designated tasks itself without the human interference. The autonomous robot or more scientifically called as artificial intelligence robot able to ‘think’ when making decision and ‘act’ based on the decision make. The mobile robot will know how it should move and ‘act’ to move as a response. It normally obtained the raw data that captured by the mobile robot hardware devices such as laser sensor, sonar sensor or camera. Figure 1 shows the basic concept of how the autonomous mobile robot works.

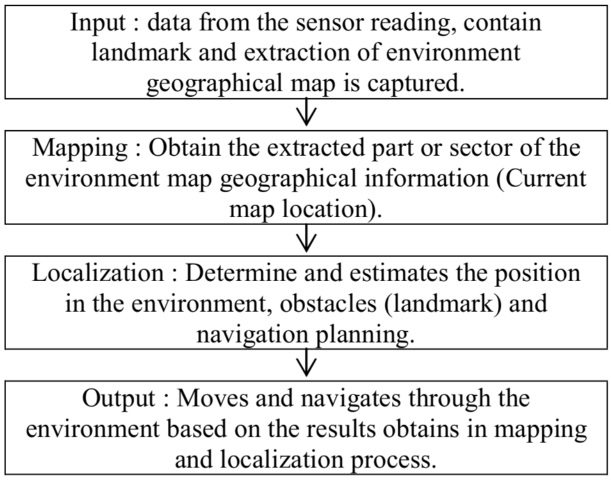

Fig. 1. General steps perform in autonomous mobile robot

Many researches were conducted to make the mobile robot able to explore without any prior knowledge on environment it explores, increasing the estimation accuracy and reducing the error occurs during exploration. Several techniques have been introduced in finding the suitable technique to solve challenges faces in autonomous mobile robot as mentioned earlier. Normally, the technique used only focuses on one of the robot functionality that is either mapping or localization process. Also, the aim is to improve and optimize the mobile robot performance in terms of landmark estimation, robot posterior and location estimation, effective path planning and reducing error made by the mobile robot. Then, when Simultaneous Localization and Mapping (SLAM) are introduced [1], it became the most recognized technique by researcher. Nowadays, SLAM became the fundamental element in most recent study conducted in robotic field.

This paper is organized as follows. Section II review the SLAM background and it process overview. Section III discuss about recent development of SLAM. Section IV explains about SLAM features. Section V discuss about

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SLAM fundamental implementation. Section VI discuss about issues in SLAM. Section VII is the paper conclusion.

II. SIMULTANEOUS LOCALIZATION AND MAPPING (SLAM)

Simultaneous Localization and Mapping (SLAM) is technique used for mobile robot to build and generate a map from the environment it explores (mapping). The generated map then is used to determine the robot and surrounding landmark location and make an appropriate path planning for the robot (localization). The process of mapping and localizing in SLAM is done concurrently where the mobile robot relatively creates the map. The created map is used to calculate and estimate landmark position and mobile robot trajectory [2]. SLAM advantage is that it able to generate geometrically consistent environment map and localized robot position and landmark concurrently. These became the major factors which makes SLAM the most appropriate technique in autonomous mobile robot field [3].

The idea of SLAM problem was introduced in [1] which originates or inspired from the previous work done in [4]. Work done in [1] introduced the first SLAM algorithm called as EKF-SLAM. This SLAM algorithm implements an Extended Kalman Filter method in solving the SLAM problem. The approach was using probabilistic method to limit the impact of inaccurate sensor reading on the accuracy of the resulting map of mobile robot [5]. Since that, it became the standard implementation in SLAM and most of the new SLAM methods introduced also implement Extended Kalman Filter method in solving the SLAM problem. Figure 2 shows the overview of SLAM process and figure 3 shows block diagram of SLAM process.

Initial map of the environment is generated and extracted from the sensor to obtain initial information about the environment.

↓

Initial mobile robot position that is starting point, surrounding landmarks are then being computed and extracted based on the generated map and information of the environment before it starts to move.

↓

Mobile robot starts to moves and during movement, mapping and localization process is executed recursively and new environment surroundings map are extracted to update the mobile robot knowledge.

↓

New landmark will be observed and extracted based on the new extracted map of surrounding environment in mobile robot new position.

↓

The mobile robot will attempt to associate the new observed landmark with the previously seen landmark. As the new landmarks were observed, it is used to update the new mobile robot position.

↓

Mobile robot navigate through the environment based on the updated information it received and the mobile robot navigation planning will changes each time it receive new information.

Fig. 2. SLAM process overview

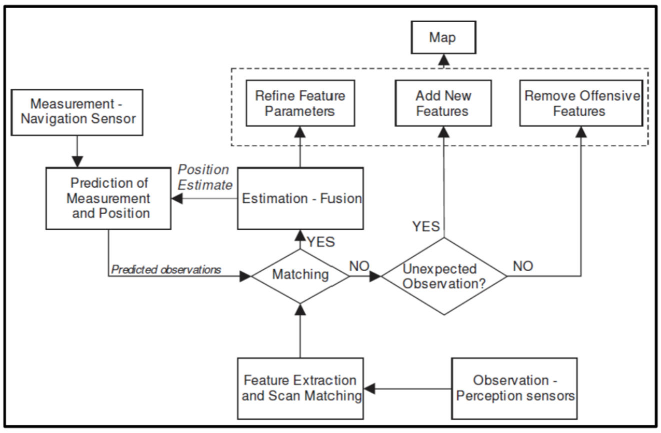

Fig. 3. Block diagram of SLAM process [6]

III. EVOLUTION OF SLAM

Throughout the past decades since the introduction of SLAM technique in artificial intelligence mobile robot, SLAM continues to evolve exponentially. The evolution of SLAM keeps continues until today to improve the efficiencies and qualities of SLAM algorithm in terms of precision, estimation and error rate reduction.

In 1986, the work done in [4] introduces the concept of implementing the estimation of spatial uncertainty at IEEE Robotics and automation Conference in San Francisco. It became the starting point to the pre-development of SLAM technique. Then, in 1991, [1] develop SLAM technique based on the previous work done in [4] which using probabilistic approach in solving SLAM problem. This work introduces the implementation of Extended Kalman Filter method which later introduces the first SLAM algorithm that is EKF-SLAM. In 2001, [7] propose the usage of the MMW (Millimeter Waves) to build relative maps which concern on the environment mapping process of the mobile robot.

In 2002, [8] introduce the FastSLAM algorithm. This SLAM algorithm is one of the most recognized SLAM methods after EKF-SLAM. The idea of FastSLAM is by using hybrid approach which integrate Particle Filter and Extended Kalman Filter approach. Such implementation gives FastSLAM popular for it higher data accuracy. A year later, FastSLAM evolve which resulting to the second version of FastSLAM called as FastSLAM 2.0 [9]. The modification done in FastSLAM 2.0 is that the proposal distribution must relied in both previous pose estimation and also the actual measurement of the mobile robot while first version of FastSLAM only relied on previous pose estimation of the mobile robot.

In 2006, [10] proposed the smoothing method called as Square Root Smoothing and Mapping (SAM) for the improvement of mapping process of mobile robot. The technique uses the Square Root information smoothing approach in solving SLAM problem in improving mapping process efficiency. In 2008, [11] introduce a new technique which provides robust algorithm based on scale unscented transformation called as UFastSLAM. The technique proposed improve the FastSLAM method introduced earlier in [8] by using scale unscented transformation algorithm approach. In 2009, [12] introduce new technique in solving SLAM problem that is called as Differential Evolution technique.

Most of the introduced SLAM algorithm addresses a single-robot mapping and dealing with static environment [13]. However, recent SLAM development shows that numerous implementations have been applied into SLAM to deal with more dynamic environment and multiple robot navigation. SLAM algorithm keeps improving and enhanced it reliability from the first introduced SLAM algorithm until recent SLAM development. Different SLAM algorithms try to tackle and improvise different aspects in SLAM problems. The ultimate objective in SLAM algorithm is to realize the challenge of optimum navigation, localization and mapping that is capability of mobile robot to self-explore with no human interference in dynamic environments given a time period.

IV. Feature of SLAM

There are three main features in SLAM that is mapping, localization and navigation.

A. *Mapping (Environment Representation)*

Before the mobile robot starting to explore or navigate in unknown environment, it requires map on the environment it want to explore as prior knowledge. Mapping gives capabilities for mobile robot to generate a map of the environment using the hardware sensor to receive the data of the environment [14]. From the data, a map is generated and the types of map representation are topological, geometric, grid or mixed map [3]. Then, it will be used by mobile robot to localize and recognize its own position and landmark.

B. *Localization (Location Estimation)*

Localization is one of the SLAM features as the mobile robot able to calculate and estimate landmark position and mobile robot trajectory based on the generated map from the mapping process [3]. Localization means that the mobile able to 'think' itself by calculating and estimating it trajectory, landmark location and able to recognize nearby obstacles based on the information received from the mapping process [2]. Localization makes the robot able to recognize its own location, surrounding environment and avoid any nearby obstacles.

C. *Navigation (Path Planning)*

These features combine both mapping and localization features where the mobile robot makes an appropriate path planning from the information received during mapping and localization process. As the mobile robot navigates throughout the environment, mapping and localization process were executed recursively in order to update the mobile robot knowledge on surroundings environment [2]. The mapping and localization process are to ensure that the mobile robot be able to navigate on surrounding environment efficiently. The characteristics of navigation planning made by the mobile robot are make appropriate path based on information received, response to surrounding environment and be able to backtrack to origin point or starting point after exploration.

V. SLAM Fundamental Implementation

A SLAM objective is to make robot relatively generate a consistent map of an environment and at the same time use the generated map to estimate the location of the landmarks and robot. An interesting fact of SLAM is that it does not require any prior knowledge of mobile robot and landmarks location since the platform trajectory and landmarks location are estimated and computed online. Suppose a robot exploring through and environment, using a sensor device to observe and estimate the landmark location in the environment. Figure 4 shows the SLAM fundamental implementation that depicts the SLAM state of the art.

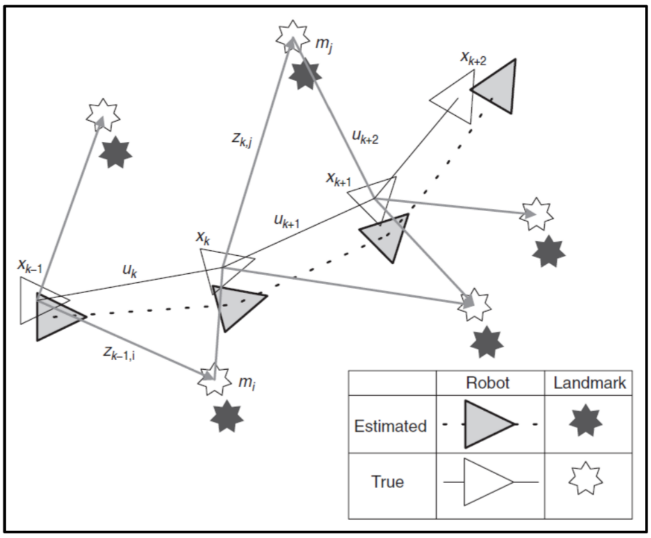

Fig. 4. SLAM state of the art [2]

Based on the Figure 4, both robot and landmarks location are estimated simultaneously. A true robot and landmarks location are unknown and not measured. Observations done are between true robot and landmark locations. Following variables are defined at time k [3]:

k	:	Time instant.
x_k	:	Robot location.
X_k	:	Sequence of robot location or path.
u_k	:	Odometry between time k - 1 and k.
U_k	:	Sequence of robot odometry or relative motion.
m_i	:	Map of the comprised of landmarks, objects, surfaces and their respective locations.
Z_k	:	Sequence of measurements between robot and landmarks assuming one measurement per time step.

For robots, x_k are comprises of its position in the plane (Two dimension vector) and orientation in the plane (Third dimension vector). For the robot path X_k, it is taken from time $k = 0$ and defined as:

$$X_k = \{ x_0, x_1, x_2, x_3, \dots, x_k \} \quad (1)$$

For the relative motion U_k between two time steps, k - 1 and k, it is defined as:

$$U_k = \{ u_0, u_1, u_2, u_3, \dots, u_k \} \quad (2)$$

It is not appropriate to relied only on robot odometry U_k to determine robot location within a plane because in real application, it suffers the lack of precision required for accurate localization. It is due to the structure of environment surfaces and robot misbehaves action such as wheel slippage. Taking into consideration, robot cannot only depend on odometry measurement alone but also relies on continuous sensory measurement Z_k for more accurate true location estimation. The sequence of sensory measurement Z_k per time step is defined as:

$$Z_k = \{ z_0, z_1, z_2, z_3, ..., z_k \} \quad (3)$$

Once all the required information are obtained and defined, next steps are building a map view of environment and location prediction. SLAM technique is using probabilistic approach which applies a probability distribution to predict the robot and landmarks location from the generated map. The probability distribution form, P is defined as:

$$P(x_k, m \mid Z_k, U_k) \quad (4)$$

From here, it can be read as the probability of the position at time k and map given the history of measurements and odometry data [15]. In addition, it also requires additional relationship which is observation model. Observation model identifies the relationship between the robot position x_k and odometry u_k which is defined as:

$$P(x_k \mid x_{k-1}, u_k) \quad (5)$$

Another model required is motion model. Motion model identifies the relationship between sensory measurements z_k, map environment m and robot position x_k which is defined as:

$$P(z_k \mid x_k, m) \quad (6)$$

In general application, robot is able to detect landmark range, relative direction and the unique identity in typical environment. These understanding can be used as a basis to derive a measurement model. By applying probability distribution into measurement model, it can be defined as:

$$P(z_k \mid x_k, m) \sim N(h(x_k, m), Q_k) \quad (7)$$

where $h(x_k, m)$ is an arbitrary function that represent sensory equipment operation, N is two dimensional normal distribution and Q_k is two dimensional noise covariance. Function h returns a computed measurement by using the position and environment map as inputs [2].

For the motion model, a normal distribution is applied which focuses on kinematic motion model covariance. The motion model derivation is defined as:

$$P(x_k \mid x_{k-1}, u_k) = N(g(x_{k-1}, u_k), R_k) \quad (8)$$

where $g(x_{k-1}, u_k)$ is standard kinematic function and R_k is a three dimensional noise covariance. Function g combine previous position x_{k-1} and the position changes in terms of odometry u_k to return the new position x_k [15].

The robot will update its position and landmark measurement at previous time step k - 1 with improved precision from the data it gathers from other landmark and previous robot position at time step k. The process is done continuously to update the robot measurement until the robot finish its exploration in the environment.

VI. Issue in SLAM

There exist several major issues arise in SLAM that is uncertainty, correspondence, data association and time complexity. Each problems mentioned will be discussed to point out it impacts to the SLAM.

A. *Uncertainty*

In uncertainty, there are two major issues known as location and hardware uncertainty [16]. Both issues hugely affect to the SLAM capabilities in performing it functionality. Location uncertainty is one of the difficulties faces by SLAM as it determines how capable the mobile robot can handle the multiple paths happens in environment location. It is simple for the mobile robot to move from one point to another point in single linear path and trackback to origin point as it path is linear and easily recognized [15]. However, in real environment, there are multiple paths for the mobile robot to travel and navigate in environment form one point to another. Hence, such problem causes the high degree of location uncertainty for the mobile robot to choose the appropriate path and recognize it actual or absolute position. In hardware uncertainty, noises of hardware used in the mobile robot components lead to the information extracted were inaccurate [15]. Such inaccurate information received will be calculated and processed to recognize the mobile robot position, landmark and other related information.

B. *Correspondence*

Correspondence is considered as the biggest problem faces in SLAM since these problems greatly affect the landmark identification process in SLAM. The reason is that how capable of the SLAM to distinguish one particular landmark are unique and different from other identified landmarks [17]. For simple example, two different obstacles (landmarks), like two rocks which is rock A and rock B. Both rocks have similar shapes but the only different is that rock A are slightly bigger than rock B. Human can easily recognize the difference but not the robot. As we know, mobile robot does not have a human ability to differentiate landmark identities easily, which is why it heavily depends on the hardware to view or measured the environment [15]. Due to the environment information were extracted from mobile robot hardware such as laser sensor, it is difficult for the mobile robot to recognize the new landmark whether it is differ or same from previously observed landmark.

C. *Data Association*

In data association issues or problem, it does concern on the SLAM capabilities to makes the mobile robot able to return to its origin point or previously mapped area after a long exploration of the environment [16]. The difficulties part were point out when the mobile robot attempt to associate the current landmark with previously observed landmark in order to return to previous origin point or mapped area. Data association process was used to estimates the landmark correspondence of mobile robots to backtrack to its origin point based on the previous map and identified landmarks [17].

D. *Time Complexity*

Time complexity issues is about the difficulties or problem rise is the how fast the implemented SLAM algorithm or methods to process, calculate and compute the received information to produce expected results that will be used by the mobile robot [16]. As we know, SLAM carries out mapping and localization process concurrently and recursively during navigation. Such multiple processes executed concurrently in a short amount of time need to be handled and managed effectively. Hence, the performance and time complexity of the SLAM algorithm or methods become the key element to produce reliable results for the mobile robot to successfully explore the environment and reducing the error rate [17].

VII. CONCLUSION

Various studies have conducted by researchers to find the best technique in realizing an autonomous mobile robot. Most work is primarily focus on one distinguishing process which is either mapping or localization. This is because due to limited technology and knowledge at that time. However, as time passes, a new breakthrough technique has been introduces that is called as SLAM. SLAM proves that it is possible for the autonomous mobile robot to concurrently execute the mapping and localization process to enhance the robot efficiencies during exploring a dynamic environment without human interference.

SLAM technique becomes a huge achievement in solving the autonomous mobile robot problem and it also considered as ‘holy grail’ in artificial intelligence mobile robot fields. The effectiveness of the SLAM in solving problem of mobile robot mapping and localization really gives a huge contribution to the self-exploratory oriented mobile robot. In theoretically, SLAM technique is considered as a completed solution, however in practical view there are still numerous number of issues and problems as mentioned earlier that needs to be considered in SLAM. In summary, SLAM really provides a promising solution, but how far does the developed SLAM algorithm can effectively fulfill the main objective of SLAM technique in making the mobile robot truly autonomous. There are still several questions lingering regarding to the fundamentals aspects in SLAM and it implementation. Hence, a deep and thorough understanding regarding SLAM and it importance to the artificial intelligence mobile robot is necessary. With recent achievement in SLAM development, it is expecting that in the future that SLAM can be easily implemented in different possible domain with promising results.

In our future works, we are proposing the idea of integrating the soft computing technique into SLAM algorithm which resulting the hybrid approach. Soft computing is technique used to solve the computational complexity problems and mathematically intractable problem [18]. It provides flexible and reliable processing method in solving SLAM problem. The main objective of this idea is to improve and optimize the performance of SLAM algorithm in terms of robot and landmark precision, estimation and error rate reduction. This idea is not a new approach since there are several works done has proposed this idea as in [19-20]. The proposed hybrid solution is the integration of SLAM algorithm that is FastSLAM algorithm with soft computing technique that is genetic algorithm [19] and particle swarm optimization [20].

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