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Survey on Robot Vision: Techniques, Tools and Methodologies

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Abstract

Robotics and Vision demands Artificial Intelligence (AI) techniques to develop devices which are capable of interacting with the physical world. The accuracy of AI devices such as Robot interfacing with physical world purely depends on how effectively the devices perform the operations. The effectiveness of the Robot is sensitive to the vision techniques adopted in the application. So the vision techniques and methodologies play significant role in design of autonomous and self controlled Robots for real life applications. Thus this article presents the review of various Robot vision techniques and methodologies adopted currently for processing images captured by robot vision modules that further enhances the accuracy of Robot. Finally, the survey on image processing methodologies adopted by robot vision is summarized to identify the optimal method for future research on robot vision.

Keywords: Robot Vision, Holonomic, Non-holonomic, Path planning, Path tracking, Optimal navigation, Visual servoing.

INTRODUCTION

The feature of Robot vision was developed in the 1980s and 1990s. A programmed Robot which is capable of visualizing the surrounding environment was developed by the researchers. The robot vision enables the self controlled robots to track and detect many objects at the same time. Robot Vision is a combination of camera hardware and computer algorithms which process captured visual data. The data process sequence of Robot Vision is shown in figure 1.

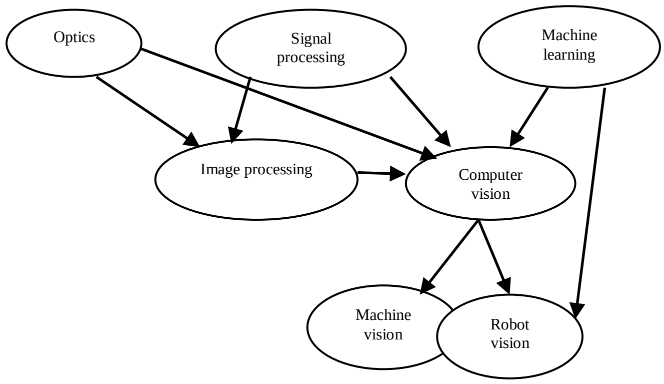

Figure 1: The data process sequence of Robot Vision

In figure 1, the *signal processing* extracts the information from the electronic signals which may be analog or electrical. The *image processing* phase process the image for improving the quality of the image that can be processed further through *computer vision* for identifying the specific object in the processed image. *Pattern recognition* is the process of identifying a specific pattern in the processed image and compare with predefined data stored which is known as *machine learning*. *Machine Vision* refers to the industrial use of vision for automatic inspection, process control and robot guidance. *Robot vision* refers to incorporating the aspects of robotics into its techniques and algorithm such as kinematics, reference frame calibration and robots ability to physically effect the environment. Visual Servoing is an example of Robot Vision. The data processing schemes, input and output are summarized in table 1.

Table 1: Summary of Data Processing Schemes

Data Processing Scheme	**Input**	**output**
Signal processing	Electrical signals	Electrical signals
Image processing	Visual Images (Gray and Color)	Images
Computer vision	Visual Images	Information/features of Images
Pattern recognition/ machine learning	Information/features	Information
Machine vision	Images	Information of images in digital data
Robot Vision	Images	Response on Actuators

The summary of domain based data processing features are demonstrated in table 2.

Table 2: Summary of domain based data processing

Domain	Data type	Feature extraction
Image processing	Signal	Signal strength, quantitative Information such aspeak location.
Computer vision	Image / video	Image qualitative/quantitative information, such as size, color, shape, classification.
Machine learning	Any feature signal from e.g image, video, sound etc	Signal qualitative/ quantitative information, image.

The robotic technology finds its application in many fields with added features like three dimensional support, removal of unwanted data (i.e filtering) or detection of light intensity applied to an object. Its applications also include

- Identifying the object type and its location
- Tracking a moving object
- applications for security and surveillance
- identifying the defective parts
- warfare applications
- helping the robot to move from one position to the specified position
- for interaction in computer-human interaction

LITERATURE REVIEW

Visual Servoing

Visual Servoing (VS) is a technique where a robot is being controlled with the help of a visual sensor. These Visual Servoing techniques are demonstrated in the following methods [1][2]. Image-Based Visual Servoing (IBVS), Position/Pose-Based Visual Servoing (PBVS), Hybrid approach. Two dimensional and three dimensional servoing methods are used in hybrid approaches. These hybrid servoing techniques are processed as 2-1/2-D Servoing, Motion partition-based Servoing and Partitioned DOF Based Servoing,

General approach versus hybrid approach

The General approach is a hierarchal method in which a good set of attributes are uprooted from the image, assuming that the object is a known priori. The problem that is encountered is singularity. The problem of singularity can be avoided using hybrid approach. In this approach the posture of the object is surmised, the motion information of the object is estimated using various techniques.

Visual servoing

The functional diagram of the Visual servoing is demonstrated in the figure 2.

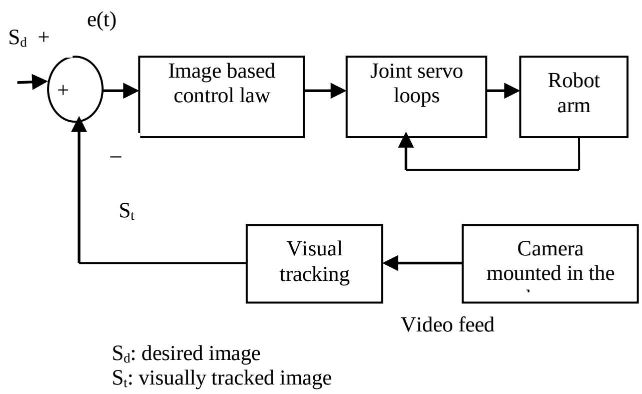

Figure 2: Functional diagram of visual servoing

In the figure 2, the image captured from the end-effect camera is given to a visual tracking system which is continuously compared with the predefined image (S_d). If there is any difference between the desired image and the captured image an error is generated. This error signal is analyzed by the image based control law. This processed input signal is given to the joint loop after which the robot arm has to reach the desired object. The camera which is fixed to the robot arm will give a feedback, so it can modify its position automatically till the task is performed.

Visual Servoing consists of two techniques.

a. Firstly attain the data from the image using the Degree Of Freedom (DOF) of the robot.

b. Secondly enumerate the geometrical values such as evaluate the posture of the target and camera specifications its location, control point application—joint movement.

Initially the authors [3] recommended a hierarchical visual servo scheme for image-based servoing. The proposed method [3] depends on the assumption that a good set of attributes of the object such as edges, corners and centroids. This method is used as sectional model in synchronous with universal models of the scene and robot. The IBVS control scheme was applied to simulation of a two and three DOF robot arm. It is assumed that the target is known priori and all features are extracted from the object. In adaptive visual servoing, the robot is purposed with a look and move servoing architecture. A Kalman filter is used to disclose the sensor errors and supervise the continuous movement of the robot.

The IBVS system assumes that the camera and the features, from which the objects are extracted, placed in the parallel plane. In [4] the researchers presented an approach of velocity control using the Jacobian relationship $\dot{s} = J\dot{v}$ for IBVS. Wherein [4], control loop is developed using feed-forward input which is obtained from model of the target velocity. The purposed system may have dynamic effects, lag in response repeatability, kinematic discrepancy, and settling time oscillations. The Jacobian matrix computes the first order partial derivative of a vector- valued function. In literature, a matrix and its determinant are referred as Jacobian when the matrix is a square matrix. The author Chaumette [5] identified two major problems with IBVS. The identified problems [5] are Servoing to a local minima and reaching a Jacobian singularity. The authors in [5] concluded that image points alone do not present good features of an image with reason of singularities. The essential finding which was highlighted by the author is the relation between local minima and unrealizable image feature movements. To obtain the information of the moving object, the primitive hybrid methods used a composition of image-based and pose-based approaches for servoing which uses either full or partial model of the object. A fine moving model polyhedral CAD model [6] is presented to obtain the object posture with respect to the camera position on the lines of PBVS. 2-1/2-D visual servoing developed by Malis et al. [7] is a well known technique that breaks down the data required for servoing into a systematic way and it decouples rotations and translations presuming the known data of the pose. Here it is assumed that the target never leaves the (FOF) Field Of View and depth is estimated using some off-line technique. This technique is mostly used than the other specified methods. The authors argue that the visual Jacobian will not have singularities during the robot motion. In hybrid approach the task is separated into two parts: main and secondary. In first task is that the attributes of interest are being captured from the FOV. The second task is to move the camera to the desired pose. It should also measure the depth of the estimate using some off-line procedure. The features that are obtained initially carries out feature modeling and model based tracking techniques. These techniques are being compared with the traditional techniques even when blockage occurs.

Evaluation Parameters for Visual Servoing

Different attributes used and their affects on visual servoing:

The image obtained from the camera is expressed in the matrix form which consists of object information. The image consists of borders of the object, attribute movements, moment invariants and image moments. The tracking of image attributes was explained in [8].Image attributes which are texture patches undergo deformation based on distant measure. The main aim is to improve the visual servoing performance by calculating depth of the axis which can be done by using Greens theorem. In this method camera calibration can be avoided when the objects are planar no depth estimate camera need to be used. Image based visual servoing (IBVS) is proved to be robust to calculated errors from the pure experimental work done by [9]. In continuation to the work [10] the errors were analyzed for 2-1/2-D visual servoing and position based visual servoing. This technique stops the error obtained from the image extracted, to propagate to the next stage that is pose estimation and servoing control. Some other additional errors arise from pose estimation and camera calibration. Therefore a more accurate depth estimate is needed in order to limit the error.

Vision-Based Model Predictive Control for Steering of a Nonholonomic Mobile Robot

A non-holonomic robot is a mobile robot that moves in the specific direction only whereas a holonomic robot moves in all the N directions. This is designed using both kinematics and dynamic constraints. The target position is identified with the help of Cartesian coordinates in two ways. Vision based tracking and vision based stabilization. This is done with the help of pan camera which is capable of remote directional and zoom control of the mobile robot.

Method and tool

A tracking system [11] has been presented based on vision techniques in association with an adaptive estimator and it estimates the mobile robot position through online. This kind of vision techniques can be implemented for both planar and non-planar scenes without matrix estimation or disintegration [12]. There are few methods presented in literature by researchers - A*daptive Sliding Mode Dynamic Stabilizing Controller* for undetermined non-holonomic dynamic mobile robot where camera is positioned at the ceiling, B*ack Stepping Technique* for dynamic feedback control law which was applied to Wheeled Mobile Robot (WMR) to perform position based visual steering. The Model Predictive Control (MPC) is the tool used for implementing this method and MPC is popularized as Receding Horizon (RH) control [13]. An accurate sensor i.e., kinect sensor is being used to identify the position and movement of the robot. Path tracking of the Autonomous Mobile Robot (AMR) was presented using learning-based Non-linear MPC (NMPC) which considered the priori vehicle structure and learned disturbance model. Kalman filter is being used in the design to minimize the mean of the squared errors.

The limitations of Brockett's result have shown impact on popular path planning and control techniques like Holonomic motion planning and control problem of WMR. Even though the destination is set, the robot will not be able to reach the exact point instead reaches to nearby position (asymptotically) by means of feedback control laws which are smooth and time invariant. In addition, the traditional MPC methods used in these papers the controller have to perform many online calculations. While the unique technique proposed by the author is a visual-based Non linear MPC added by neural network optimization and visual servoing. This controller performs the operation online even with less calculating power. A neural network was presented [15] for analyzing Linear Variational Inequalities (LVIs) and quadratic optimization of objects using projection techniques. The practice of neural network permits optimization and parallelization of hardware for efficient utilization and support.

Non-holonomic robotic model

1. Kinematics model
2. Dynamic model
3. Camera model—kinect sensor 3-D depth sensor
4. Robot camera target model

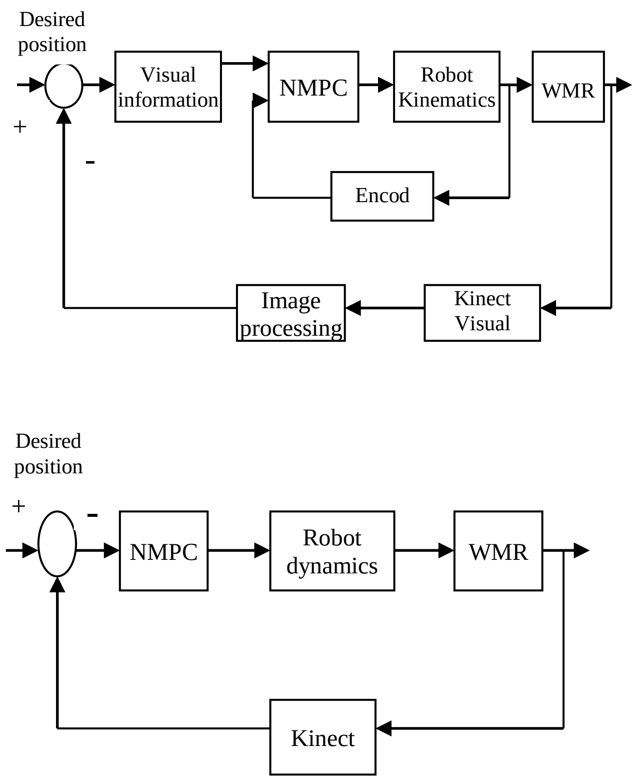

Figure 3: Block diagram of Visual servo steering control

Evaluation of NMR-MPC

The mean noise have been reduced in NMR-MPC by continuous measurement of the desired position of the robot. In NMR-MPC, the robot information and Kinect sensor measurement is continuously obtained and processed through Extended Kalman Filter (EKF) [16] to reduce mean noise error of robot movement. The current position of the robot from its reference position is represented in a 2D matrix form. The limitation of this method is that when a robot moves fast then the data retrieval becomes complex.

The Quadratic Programming (QP) presented in [19] - [21] can be solved by a traditional Quadratic Programming method QUADPROG [17] [18] available in MATLAB Optimization Toolbox. In classical QP optimization, the intricacy is directly proportional to the number of additive constraints. When MPC is correlated with the Primary-Dual Neural Network (PDNN) algorithm, the QP algorithm is similar to the PDNN algorithm. A visual steering scheme has been presented for NMR [19] by combining NMPC and PDNN methods. The optimization is achieved using PDNN which is iteratively formulated Quadratic Programming model.

Practical path planning and path following for a nonholonomic mobile robot based on visual servoing

The researchers presented an algorithm for path planning and been implemented in 3 parts.

1. At initial part of the path planning technique, the Multi-Stencils Fast Marching (MSFM) being used is not smooth and safe due to it may provoke the robot to come in contact with walls, corners and obstacles. So image processing methods are used to overcome this difficulty.
2. In secondary part, the path planning model collects the visual information and estimates the orientation and position of the robot to follow the specified path with obstacle avoidance.
3. In final part, a distributed PD-like Fuzzy Logic Controller (FLC) is presented to maintain the robot exactly on the specified path.

Over the last few years research have been going on in robot path planning, movement of robot from one point to another in a collision free environment. The two aspects that determine and clear path-planning problem are: path-planning algorithms and environment type. In the offline algorithm method Dijkstra's algorithm is being used, in the online algorithm method Fast Sweeping Method (FSM) and Fast Marching Method (FMM) is being used.

The FMM has a specific advantage over the existing methods. FMM specifically provides a narrow band which separates the grid points of unknown ones and known ones. FMM complexity in calculation is not ideal and along the diagonal direction it does not have accurate result. Therefore an approach Multi-Stencils Fast Marching (MSFM) has been introduced which is advancement of FMM. The MSFM estimates the result at each grid point by solving the Eikonal equation and repeats for all other stencils which envelope entire neighbor points to find optimal solution that flatters the up-wind condition.

The Visual Servoing techniques are Position Based Visual Servoing (PBVS), Image Based Visual Servoing (IBVS) and Hybrid Based Visual Servoing (HBVS) [22 - 25]. These visual servoing algorithms consist of two main modules. The vision sensor sends the information to the *primary module* which identifies and segregates the objects of interest or traces the object continuously in all the frames. The primary module also estimates the object location and maps it to the real world. The primary module accepts input from the camera calibration methods [22][26][27], and passes position of object to the *secondary module* which guide the robot to move in specified path. Different methods have been used with visual servoing. They include identify and segregate the detected objects including the

i. attribute-based,
ii. gradient-based,
iii. background subtraction based,
iv. statistical model based,
v. template-based, and
vi. optical flow object detection methods [28-30].

The secondary module is designed as a position controller. The aim of the controller is to dynamically adjust the camera view to trace the object [31] [32] [32].In modern dynamically changing environment one needs a controller that is able to confront the system uncertainties and parameter variations [33]. One such intelligent technique is Fuzzy Logic control [34] [35]. The Fuzzy controllers have certain leverages such as; it is low cost & simple to control. We need not know the exact mathematical model [36-38].

The author presented a design which calculates the shortest path between the robot and the target with the help of information retrieved from the sensor using the shortest path algorithm. It is also used to estimate the posture of the object using feature based and template matching methods. The robot is monitored to move only in the desired path with the help of a fuzzy logic controller which accepts posture captured and processed image as input.

Path planning and shortest path algorithm:

The methods related to fast marching technique have large numerical errors since they do not consider the diagonal points. A solution to this problem is, to use a stencil that is centered at one point only and aligned with the natural coordinate. The coordinate system is rotated several times to intersect the lattice at diagonal grid points. Another way is by using many stencils that cover the entire diagonal points in its neighboring area. Then the gradient is approximated using directional derivatives, this method is called Multi-stencils Fast Marching (MSFM). To use this method in solving path planning problem the algorithm requires three inputs: 1) the map, 2) the starting node and 3) the destined node. Therefore, there are a number of steps which must be considered;

- Firstly the size and geometric details are obtained from the captured image
- Secondly identify the start and end points
- Thirdly identify the path and the shortest path

This is implemented in two methods:

Direct planning method - it is not safe and the robot may collide.

Proposed Indirect planning method – it is safe and very less chances of collision.

EXPERIMENTAL RESULTS:

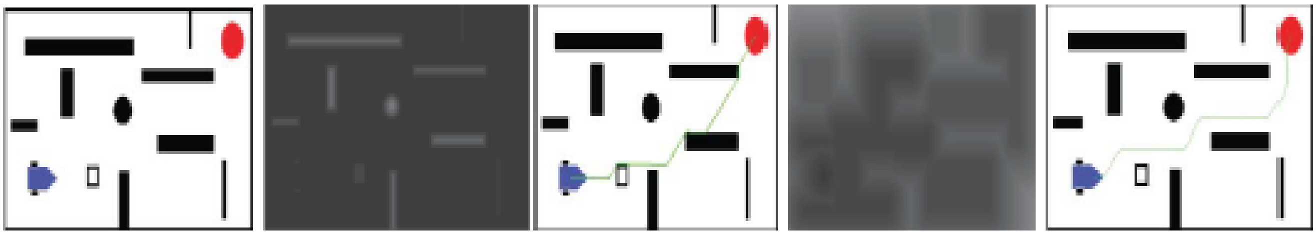

Figure 4: Direct and indirect MSFM path planning method: robot-blue, target-red, walls-black

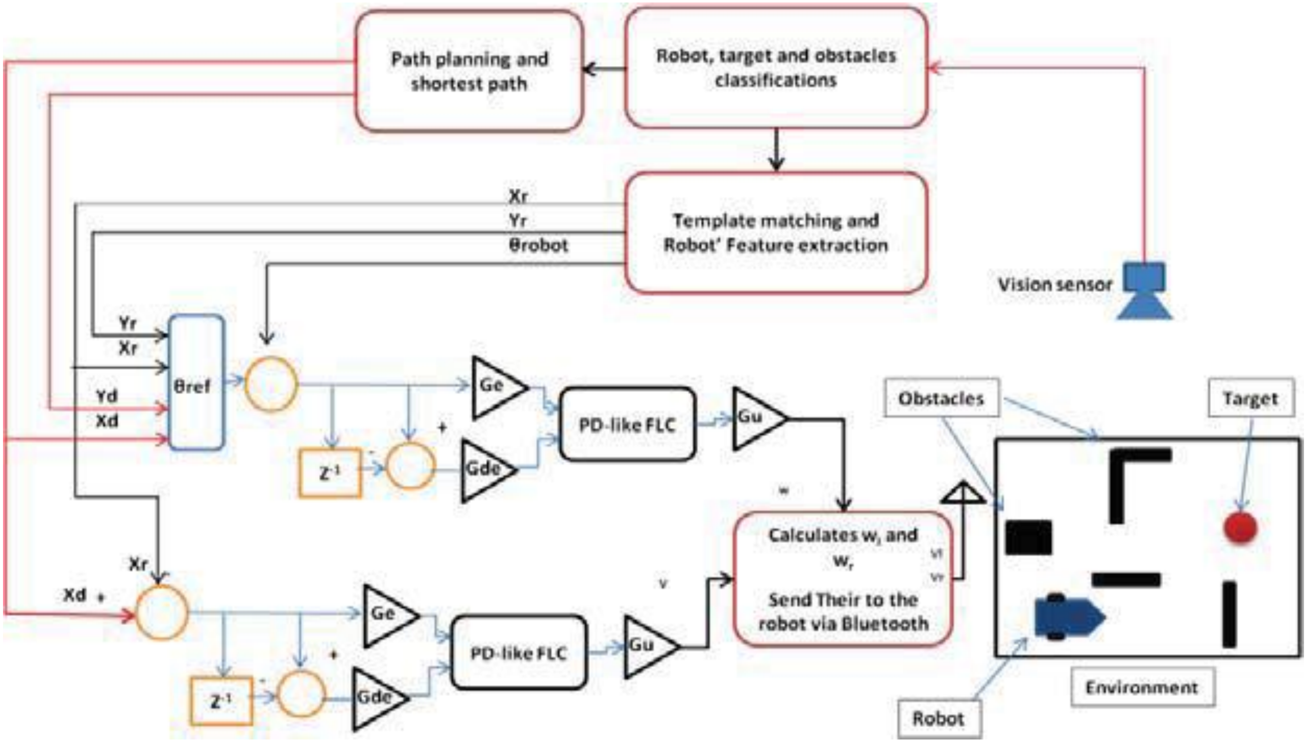

Figure 5: Path planning and robot path planning control

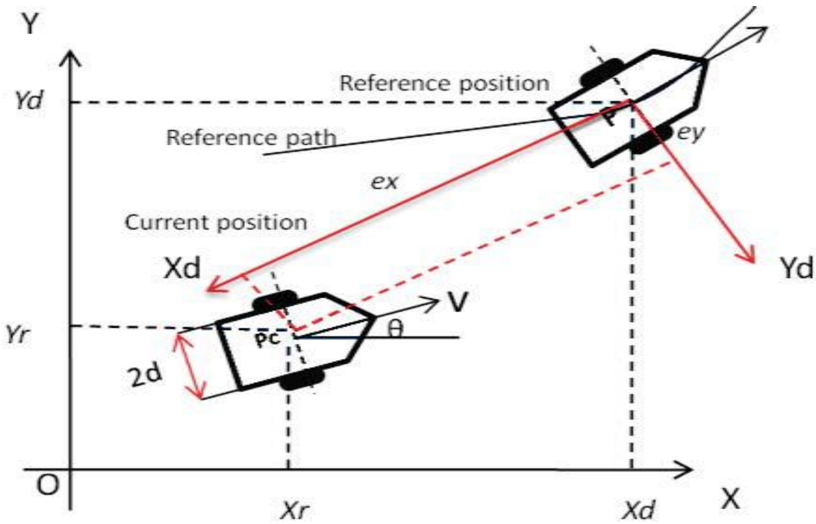

Figure 6: Tracking of virtual reference path

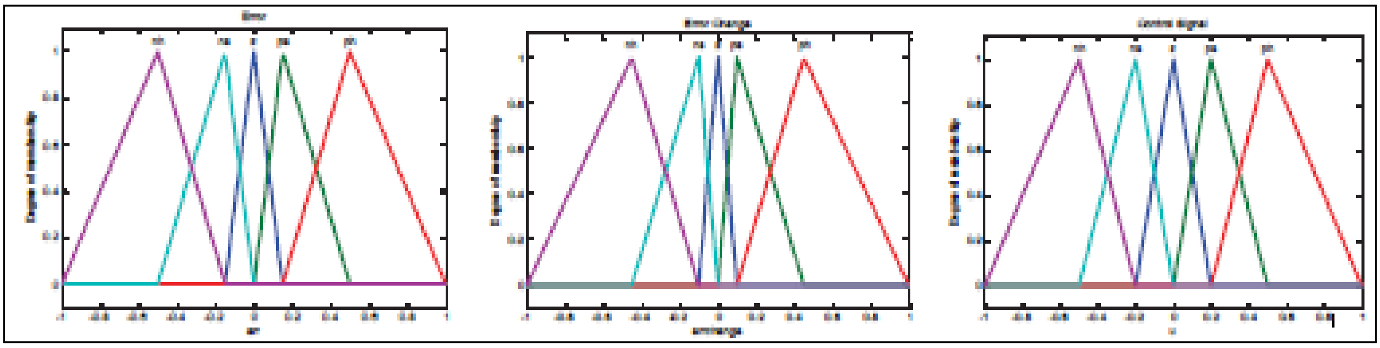

Figure 7: (a) Error MF (b) Change of error MF (c) Control MF

Optimal path planning with holonomic mobile robot using localization vision sensors

To enable instant movement of robot in all directions the authors purposed a holonomic system using 3 Omni-direction wheels. To detect the robot's position IR-projector and vision sensors are used for auto drive robots. An Autonomous Mobile Robot (AMR) is needed in a place which is difficult or dangerous for a human to move. Therefore the AMR must have the ability to perform its task and move to the next location for the next task to be performed even when the environment is hazardous and full of obstacles. These capabilities of the robot to identify and judge the environmental conditions are known as localization and navigation. The performance of a mobile robot is optimized by introducing tracking and localization algorithms while improving the sensing capabilities. Research still continues to enhance the mobile robot navigation capability.

The smart mobile robots have to be localized in indoor environment. A localization sensor that is being used for this purpose is StarGazer. The infrared rays reflected from the passive objects have an individual ID which becomes easy to analyze. The outputs (position and heading angle) produced by the system are rarely affected by the surroundings. The StarGazer collects the position and orientation information and sends it to a personal computer via Bluetooth where the personal computer executes its trajectory tracking control to help the robot in moving along the reference path in anti clockwise direction.

Figure 8: Total composition of experimental system

The reflected infrared light from the sensor fixed to the ceiling, helps the robot to move forward from reference point to the destination point using point to point navigation algorithm. If the robot reaches the target, it will automatically fix its next target position, but due to some reason the robot has stopped at the wrong position then it will correct its next target position from that position only. This error is also being evaluated. To minimize the modeling error the relation between input and output has to be given in the form of a matrix. In the near future, since the modeling error is very small it can be easily handled.

Adaptive tracking of non holonomic mobile robots using vision based estimation and velocity estimation

They are several efforts being made for many years in the trajectory tracking control of NMR, but it still remains a problem. This is because it is very difficult to localize a robot in a dynamically changing environment using onboard sensors. Therefore a new adaptive trajectory tracking system was purposed by the author for the NMR without its position, orientation and velocity measurements; it is theoretically proved that the trajectory tracking errors are reduced to zero asymptotically. Because of the above constraints the development of mobile robotics is still under research. In the yester years many tracking controllers have been purposed – such as discontinuous controllers, time varying controllers and hybrid controllers. The previous research also includes a back stepping technique and a neuro dynamics model which is a biologically inspired trajectory control which is capable of generating smooth control signals with zero initial velocity of the robot.

Based on the literature, it is very difficult to develop a tracking controller in a dynamic and unstructured environment. The SLAM methods, generally used to localize a robot, are not suitable for applications where the task has to be performed faster; this is because when the number of visible objects is large in number then it takes a long time for a robot to localize itself. IBVS is much better option when the target is a known priori. These tracking errors can be avoided by PBVS TC methods. A trajectory TC law [41] was developed for the NMR on the basis of a trifocal tensor-based approach, but the pose and trajectory errors of the mobile robot cannot be fixed to a specific value because the controller ran in two independent loops. Therefore the two errors cannot be converged.

The PBVS TC method has been developed by considering odometry sensors, velocity measurement and visual feedback taken from the camera and orientation measurements from the IMU without direct position measurements which also has a few disadvantages. Firstly slippery wheels, secondly long time for image feature extraction due to limited FOV, thirdly the stability of the closed loop system is not accurate. These three disadvantages are avoided by the technique suggested by the author. The author specifies a newly designed PBVS TC method for NMR [39] [40], wherein an Omni directional camera was used to produce a much stable image feature extraction and improving the robustness of the controller. This overall system is completely stable because of the localization algorithm which is run outside the loop and wheel slipping is also avoided. The stability of the purposed controller can be proved by light of Lyapunov theory. The performance of the controller is validated by conducting three kinds of real-world experiments on a differential drive wheeled robot.

The author encountered few random errors during implementation due to non accurate scaling, misalignment of the sensor axis and non-zero biases in Inertial Measurement Unit (IMU). This is because the purposed controller relies on angular velocity, orientation of the robot and precision of acceleration. The mean error have been reduced to zero asymptotically. The literature suggested that the robustness of the controller can still be improved and extend the applications to unmanned water surface robots and unmanned aerial vehicles in order to bring a short solution for the trajectory control problem in the field of mobile robotics.

REVIEW AND DISCUSSIONS

S.No	Methodology	Techniques	Tools	Description
1	Visual Servoing	IBVS, PBVS	Kinect sensor for localization	Measure the error in image space, calculate the image Jacobian, calculate the inverse Jacobian, and update the new joint values to keep the robot in the specific position and orientation.
2	Vision based predictive control	Vision based tracking and vision based stabilization	Model predictive control	Receiving the continuous input from the kinect sensor, combined with the EKF is able to estimate the position and orientation of the robot and stored in a 2D matrix form.
3	Practical path planning and path tracing robot navigation algorithm	MFMC. Estimating the position and orientation, FLC.	Offline and online algorithms are used	The destined object is clearly identified by filtering the other unwanted part of the captured image; it is able to identify the shortest path between the robot and the target.
4	Optimal path planning	Tracking and localization	Star gazer localization sensor	Omni wheeled robot is designed to provide smooth movement. The localization sensor is used to identify the infrared image reflected from the nearby objects with the help of RS 232. It helps the robot to move from reference point to the destined path.
5	Adaptive tracking	Vision based estimation and velocity estimation	Trajectory controller	The robot velocity and acceleration and orientation are estimated by a tracking controller to bring the mean error to be zero asymptotically.

CONCLUSION AND FUTURE SCOPE

Visual Servoing measure the error in image space, calculate the image Jacobian, calculate the inverse Jacobian, and update the new joint values to keep the robot in the specific position and orientation. Vision based predictive control receive the continuous input from the kinect sensor, combined with the EKF to estimate the position and orientation of the robot and stored in a 2D matrix form. Practical path planning and path tracing robot navigation algorithm identify objects clearly by filtering the unwanted part of the captured image and also identify the shortest path between the robot and the target. Optimal path planning uses localization sensor to identify the infrared image reflected from the nearby objects with the help of RS 232. It helps the robot to move from reference point to the destined path. Adaptive tracking estimate the velocity and acceleration and orientation by a tracking controller to bring the mean error to be zero asymptotically. As the literature suggested that adaptive tracking of non holonomic mobile robots can have the scope for optimizing accuracy and effectiveness of the self controlled robot through vision based estimation. So the future research need to be concentrated on development of adaptive tracking methods for self controlled mobile robot using effective vision techniques while incorporating security standards to avoid malpractices.

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