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Educational hands-on testbed using Lego robot for learning guidance, navigation, and control^{*}

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Abstract: The aim of this paper is to propose an educational hands-on testbed using inexpensive systems composed of a Lego Mindstorms NXT robot and a webcam and easy-to-deal-with tools especially for learning and testing guidance, navigation, and control as well as search and obstacle mapping, however the extendibility and applicability of the proposed approach is not limited to only the educational purpose. In order to provide navigation information of the Lego robot in an indoor environment, an vision navigation system is proposed based on a colour marker detection robust to brightness change and an Extended Kalman filter. Furthermore, a spiral-like search, a command-to-line-of-sight guidance, a motor control, and two-dimensional Splinegon approximation are applied to sensing and mapping of a complex-shaped obstacle. The experimental result shows that the proposed testbed can be viewed as an efficient tool for the education of image processing and estimation as well as guidance, navigation, and control with a minimum burden of time and cost.

Keywords: Education, guidance, navigation, and control, obstacle mapping, colour marker detection, Splinegon, Lego Mindstorms NXT.

1. INTRODUCTION

Recently Lego Mindstorms NXT which is one of the commercial robot kits has been used for testing the robotics applications [Worrall and Mcgookin (2006); Oliveira et al. (2009)] and more actively implemented as the educational tool for teaching robotics and control engineering: to name a few, Gawthrop and McGookin (2004); Carusi et al. (2004); A. Behrens (2008); Grega and Piat (2008). Worrall and McGookin (2006) derived the dynamics and kinematics of the differential-drive type Lego robot and compared the simulation result with the real experiment case for waypoint navigation. Gawthrop and McGookin (2004) demonstrated the educational laboratory experiments using Lego systems in the field of continuous-time control systems, and Carusi et al. (2004) proposed the distance learning facility for robotics and automation by which students can remotely control the Lego mobile robots. A. Behrens (2008) presented a practically motivated course development based on controlling the Lego robots under MATLAB environment. More recently Oliveira et al. (2009) presented a SLAM(simultaneous localisation and mapping) of an indoor environment using the Lego robot with a ultrasonic sensor and a compass sensor.

The aim of this paper is to propose an educational hands-on testbed using Lego Mindstorms NXT robot using inexpensive systems (a Lego robot and a webcam) and easy-to-deal-with tools especially for learning and testing GNC(Guidance, Navigation, and Control) as well as search and obstacle mapping, however the extendibility and applicability of the proposed approach is not limited to only the educational purpose. In order to provide navigation information of the Lego robot in an indoor environment, an vision navigation system using a low-cost webcam is implemented. To make the colour marker detection algorithm more robust to brightness change, a novel modified thresholding technique are proposed using the geometrical relationship of RGB(Red Green Blue) space in this study. The position and attitude of the robot can be estimated by detecting colour markers composed of red and blue balls attached on the robot, and the EKF(Extended Kalman filter) enhances its estimation accuracy. Furthermore, a spiral-like search, a CLOS(Command to Line Of Sight) guidance, a motor control, and two-dimensional Splinegon approximation are applied to sensing and mapping of a complex-shaped obstacle. To be easily handled with by even beginners, RWTH Mindstorms NXT Toolbox for MATLAB [A. Behrens (2008); RWTH-Aachen-Univ (2010)] was selected as a programming language for the Lego robot control. The experimental result shows that the proposed testbed can be viewed as an efficient tool for the education of image processing and estimation as well as guidance, navigation, and control with a minimum burden of time and cost.

^{*} A part of this study was successfully used as a student hands-on project for Working Group 2, 'Mapping of Unknown Obstacle by Lego Mindstorms NXT', at the NATO Advanced Study Institute: Advanced All-Terrain Autonomous Systems held in Cesme, Turkey on 15-24 Aug 2010.

Fig. 1. A block diagram of the indoor vision navigation system

The overall structure of this paper is organised as: Section 2 describes an indoor navigation using colour marker detection and pose estimation filter design based on the EKF. Section 3 deals with the search, guidance, and control strategies for sensing and mapping of obstacle and also gives the obstacle approximation algorithm using the Splinegon. Section 4 contains an experimental setup and looks at the results and discussions on the experiment to evaluate the performance of the proposed approach. Lastly, conclusions and future works are given in Section 5.

2. NAVIGATION VIA COLOUR MARKER DETECTION

In the GPS-denied environments such as an indoor area, it is difficult to obtain accurate navigation information on a mobile robot. Although onboard sensors like a INS(Inertial Navigation System) can be used as an active sensor of the robot, it is costly and the error might grow fast and sometimes diverge during the integration of noisy accelerations. An alternative solution can be an indoor vision navigation system to be able to provide position, velocity, heading angle and its rate of the mobile robot. The accuracy of the vision system depends largely on camera performance, and generally to get the navigation information of target object the stereo images using multiple cameras are required for triangulation [Hartly and A. (2003)]. However, in order to reduce the cost and complexity of the system, only a low-cost webcam and two colour markers attached on the robot are used by applying a nonlinear estimation method, EKF, as a compensation for the need of multiple cameras. The EKF makes it possible to get the reasonably accurate navigation information even with a single camera by optimally tuning the information between the uncertain vehicle dynamics and the camera measurements. If required, accuracy and robustness of this vision system could be significantly improved by increasing the number of cameras or using a high quality camera. [Oh et al. (2011); Valenti et al. (2007)]. Figure 1 shows an operation procedure of indoor vision navigation system proposed in this paper, and the details of the colour marker detection and nonlinear estimation algorithm will be successively explained in the subsequent sections.

2.1 Colour marker detection robust to brightness

The precise estimation of the navigation states of the robot highly depends on the effective detection of the colour markers. It can be divided into two main stages: the colour detection and its segmentation. The specific colour is detected by using threshold parameters in a colour space and they can be represented as a colour detection map. This is then fed into the segmentation stage providing the coordinates of the center point of the marker having the largest shape detected in the map.

Fig. 2. 3D colour space and graphical description of opponent colour

The previous works detected the colour by thresholding in a RGB colour space [Oh et al. (2011)] or in a normalized RGB colour space [Zhang et al. (2009)]. They might have difficulties in coping with change of illumination and light, such as in Sampe et al. (2009) and Shah et al. (2010). To overcome the limitation of the aforementioned methods, this study proposes a different set of thresholding parameters which can be robust to most of brightness situations such as daylight, florescent light, tungsten light and shadows. The proposed robust colour detection is based on an adapted opponent colour space. A human visual system is known to be best at distinguishing colours under any type of brightness by comparing opponent colours. Using this hint, this study adopts two opponent colours: cyan versus red and yellow versus blue for detecting the red and blue colour markers. As shown in Fig. 2, each colour pixel can be expressed as a vector composed of three colour values: red(R), green(G) and blue(B) and then can be viewed as a point in a 3D euclidean space having R, G, and B axes. In other words, each colour pixel of the image captured by the webcam can be mapped into the following scalar functions representing the strength of blue and red colours.

$$f_B(\vec{v}_i) = B_i - \left(\frac{R_i + G_i}{2} \right) \quad (1a)$$

$$f_R(\vec{v}_i) = R_i - \left(\frac{G_i + B_i}{2} \right) \quad (1b)$$

where $\{\vec{v}_i = (R_i, G_i, B_i) \in \mathbb{R}^3\}$, and R_i , G_i , and B_i are the RGB values of the i -th pixel. The large values of f_B and f_R of the pixels in the RGB space represent they have the higher probability to be the desired colour. Eq. (1) is used to build the detection map for the blue and red colour markers. The colour detection maps are created by selecting a group of pixels having large values of f_B and f_R as:

$$C_{colour} = \{\vec{v}_i \mid (\text{the number of } j \text{ satisfying } f_{colour}(\vec{v}_i) < f_{colour}(\vec{v}_j) \text{ where } i \neq j) < \alpha_{colour}\}. \quad (2)$$

where $colour$ represents red or blue, and this study applied $\alpha_{colour} = 50$. In other words, the closest α number of pixels to the desired colour are selected. Since in this way Eq. (1) remains the same regardless of illumination and light changes, robustness of the colour marker detection can be significantly improved as shown in Fig. 3. The generated colour detection map is then fed into the segmentation process, which then finds the coordinate of the colour marker after finding the center of the largest shape in the map. A noise is removed by smoothing with a blur kernel followed by morphology. To reduce both processing time and vulnerability to adverse environment, a recursive target tracking method is introduced. Once the marker

$$v_l = v_0 + \delta \quad (20)$$

$$v_r = v_0 - \delta \quad (21)$$

$$\delta = k_P e + k_I \int e + k_D \dot{e} \quad (22)$$

where (k_P, k_I, k_D) are proportional, integral, and differential gains, respectively and e is a feedback error term. The gain scheduling has to be done depending on the mode change: $e = e_\psi$ for the waypoint following and $e = e_d$ for the obstacle surveillance. Students should be cautious of selecting the trim velocity v_0 and limiting on δ considering the characteristics of the motors and the friction between the wheel and floor. As an additional challenge for students, parameter identification, feedback linearisation, and nonlinear control could be tested to the motor control of differential-drive robot.

3.2 Obstacle mapping: 2D Splinegon

As an easy mapping method, the measurement points defined in Eqs. (13), (14), and (16) can be regarded as vertices of a polygon with straight line segments. However, this is unsuitable for representing a complex or curved shape of obstacle. To tackle this, Splinegon approximation has been recently applied to mapping of complex-shaped objects [Sinha et al. (in press)], which produces a set of vertices to be connected by line segments having a constant curvature. It means the line segments have a C^2 contact at the vertices to share a common vertex and the same tangents at the vertices. It is impossible to meet the abovementioned constraints at the vertices with a single arc since it has only single degree of freedom: the arc curvature. One way to solve this is to use an intermediate vertex between the original vertices which results in two arc segments of different curvatures to be designed. Figure 7 shows an example of Splinegon arc segment with C^2 contact intermediate vertex. A vector sum from the start vertex v_s to the end vertex v_f must yield:

$$c\mathbf{t}_c = b_s\mathbf{t}_s + (b_s + b_f)\mathbf{t}_I + b_f\mathbf{t}_f \quad (23)$$

where $\mathbf{t}_I$ is the tangent vector of the intermediate vertex, and $(\mathbf{t}_c, c)$, $(\mathbf{t}_s, b_s)$, and $(\mathbf{t}_f, b_f)$ are the tangent vectors and the lengths of the chord, the start vertex and the finish vertex, respectively. The detailed construction principle can be found at Chap.5 of [Lazarus (2009)] including solutions for $\mathbf{t}_I$, its bounds, Splinegon shape parameterisation, vertex selection and placement.

Fig. 7. Splinegon arc segment with C^2 contact intermediate vertex [Lazarus (2009)]

4. EXPERIMENTAL EVALUATION

4.1 Experimental setup

Figure 8 shows the overall block diagram of the experimental setup considered in this study, which requires only a Lego Mindstorms NXT kit, a webcam, and two laptops. The webcam (Logitech C500) gives the vision information for the Lego robot motion to a vision laptop via USB communication, in which the colour marker detection and EKF algorithms compute and deliver the navigation information of the Lego robot to a control laptop via TCP/IP communication. At the same time, the Lego robot collects the ultrasonic distance to the obstacle in the area interested and sends it to the control laptop. Then the control laptop decides the control command for the left and right motors of the Lego robot using the navigation information of the Lego robot and the measurements of the ultrasonic sensor and delivers it to the Lego robot via Bluetooth communication. The Lego robot is designed using the five NXT components shown in Fig. 9: a NXT brick, an ultrasonic sensor, and three interactive servo motor for rotating the left/right wheels and the ultrasonic sensor. An arbitrary obstacle is simply made using papers and boxes inside the area interested.

As a brain of the Lego robot, the NXT brick shown in Fig. 9(a) is based on 32-bit ARM7 microcontroller with 256K FLASH and 64K RAM and 8-bit AVR microcontroller with 4K FLASH and 512 Byte RAM. It is supported by USB 2.0 or Bluetooth communication and operated by a rechargeable lithium-polymer battery. Although there are many options for embedded programming of the NXT brick such as NXT-G, NXC, NBC, etc., RWTH - Mindstorms NXT Toolbox for MATLAB [RWTH-Aachen-Univ (2010)] is selected as an interactive and time-saving tool for students. By adopting this, a host computer can control the Lego robot via a direct communication between the NXT robot and the MATLAB main engine with the direct use of the MATLAB math functions and other toolboxes. Since debugging the code is easy, and low-level functions and direct commands are encapsulated, the selection of this toolbox is useful for the course development for beginner students.

Fig. 8. A overall block diagram of experimental setup

Fig. 9. NXT components used in the testbed (thanks to <http://mindstorms.lego.com/>)

4.2 Results and discussion

The experiment was done in the small office room whose the size of the area interested is 0.9m-by-1.7m. At first, the Lego

robot starts the spiral-like search from the left-bottom corner of the area and successively moves to the left-top and right-top corners which are marked as red dots in Fig. 10(a). The CLOS guidance and motor control for the waypoint following works well, and the colour marker detection algorithm with the EKF gives the accurate navigation information of the Lego robot as displayed in the left-bottom corner of Fig. 10. At

Fig. 10. Experimental result of testbed using Lego robot

the right-top corner the Lego robot detects the obstacle by rotating its ultrasonic sensor, and the measurement points on the obstacle are marked as green circles in Fig. 10(b). After detecting the obstacle, the Lego robot approaches to another red waypoint near the obstacle as shown in Fig. 10(b). Once arriving that red waypoint, the Lego robot starts the surveillance clockwise around the obstacle. Then it periodically detects and saves the detection points using the measurement of ultrasonic sensor as shown in Fig. 10(c) in which blue and red circles represent the positions of the Lego robot and the detection points, respectively. The motor controller keeping a certain distance from the obstacle works appropriately for the obstacle surveillance. After circling around the obstacle by 360 degrees, the Splinegon is drawn as a cyan line using the detection points stored during the obstacle surveillance as shown in Fig. 10(d). Although the resulting shapes of the Splinegons drawn during two times of circling is not exactly identical to that of the original obstacle, the overall tendency of the obstacle surface shape is reasonably reflected. Through this experiment using a webcam and a Lego Mindstorms NXT robot, students can learn a concept and design process for guidance, navigation, and control as well as mapping and vision processing.

5. CONCLUSIONS AND FUTURE WORKS

This study proposed an effective educational hands-on testbed so that students can learn a concept and design process for guidance, navigation, and control as well as mapping and vision processing. The proposed testbed is also fascinating in view of cost and simplicity since it is composed of a webcam, a Lego Mindstorms NXT robot, and two laptops only. Its extensibility is another merit since it can include more sophisticated guidance, navigation, and control techniques. As a future work, the error analysis and correction of the ultrasonic sensor should be done, and this testbed will be used as a course work and

extended to more complex system using multiple Lego robots for verifying cooperative control and estimation strategies.

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