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An Integrated Stereo Vision and Fuzzy Logic Controller for Following Vehicles in an Unstructured Environment

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Abstract

This paper demonstrates the concept of adaptive cruise control and vehicle following where by a safe distance is maintained between vehicles. A follower robot identifies a leader by using a stereo vision camera that determines the distance between the robots. The speed and direction of the robot are controlled by fuzzy logic controllers. The system performs considerably well in unstructured environments and exhibits good straight line performance. We put forward our framework for comparative analysis with alternative controllers.

1 Introduction

Adaptive Cruise Control (ACC) extends the concept of cruise control by adapting the speed of a vehicle so as to maintain a safe speed and distance between vehicles. Vehicles with ACC autonomously slow down or speed up so that they are not too close or far from the vehicle in front. ACC was first brought to the market by Toyota in 1998 with the Progres model and more recently VW, Volvo and Ford have incorporated this technology during production. A fleet of autonomous taxis have been trialled in Daventry that use ACC to follow other taxis when tailing behind them. This paper demonstrates the current state of the art in Intelligent Transportation Systems and presents an experimental methodology for comparative analysis of control methods.

A follower must be able to detect a leader in order for it to be followed. Our approach uses machine vision to detect the leader. This has previously been done by recognising features such as vehicle symmetry [7], shadows [10], edge detection and colour [13]. The techniques for such approaches range from artificial neural networks, support vector machines to clustering al-

gorithms. We aim to reduce the computational complexity of the recognition problem and have done so by recognising a distinct colour of a pink ball attached to the vehicle rather than the vehicle. Histograms have been applied to real time robotic vision for recognising colour features as well as the location in cluttered environments [18]. The RoboCup has seen many approaches for recognising a pink ball in a football game, these include colour recognition with thresholding [1] as well as circle detection using the Hough Transform, ball detection using wavelets and independent component analysis [8] and geometric primitive detection with genetic algorithms [17].

A follower must also be able to determine the distance to the leader, for this we propose the use of machine vision, alternative methods include radar, sonar. Monocular vision can determine depth by using visual cues such as size of objects. Stereo vision can determine depth by stereopsis as well as artificial neural networks [5] and dynamic programming. Stereo vision has been used specifically for vehicle following with the BART (Binocular Autonomous Research Team) system [4].

In this paper the robot's speed is controlled with a fuzzy logic controller. Nissan first published their research into utilising fuzzy logic for speed control [12] of vehicles in 1983. This was later developed further into ACC by [11] for Daimler-Benz AG (Mercedes-Benz). For controlling the direction of the robot visual servoing has been applied to vehicle following [3, 2] as well as trajectory planning [4]. Waypoints have been applied in a tropical jungle [14] with a 12-ton skid steer autonomous vehicle, they experienced issues with occlusions in the line of sight and also uneven terrain changing the direction of sensors i.e. aiming into the ground. Daimler-Benz AG [16] used potential fields with visual sensors but it was found to be unsafe.

The remainder of this paper is structured as follows; Section 2 presents an overview of the system with detailed discussions of its key

components. Section 3 discusses the experimentation. Section 4 presents preliminary results. Section 5 discusses our conclusions and section 6 presents future research.

2 The System

Here we present an overall description of our framework and describe key features of its architecture. Two robots act as leader and follower, see Figure 1.

We use MobileRobots P3-AT robots running Linux, which have skid-steer locomotion that is suitable for unstructured environments; indoor and outdoor. A pre-calibrated, stereo vision camera (PGR Bumblebee) mounted on the follower captures images of the environment. The images are processed to identify the leader, calculate the position and distance to the leader relative to the follower. Two fuzzy logic controllers use the leader's location to determine the follower's change in speed and direction. The robot's vision system tracks the movement of the leader by mounting the camera upon a pan tilt unit.

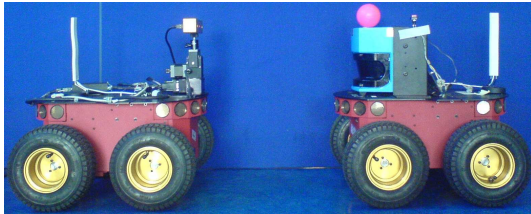


Figure 1: Robot setup

The follower has three concurrent processes for the main tasks: vision, controller and PTU. The controller forks execution for the other two processes and inter-process communication is achieved with POSIX shared memory, Figure 2 illustrates the communication model. The distance between leader and follower Z is passed directly to the controller while the local position of the leader $\theta_{v_l}, \theta_{h_l}$ is passed through the PTU process to produce global coordinates $\theta_{v_g}, \theta_{h_g}$. We now discuss these individual processes in more detail.

2.1 Vision

A stereo vision camera serves three purposes: image acquisition, object recognition and reconstruction of 3D points in the environment. Images are acquired through a firewire interface in the RGB colour space at a resolution of

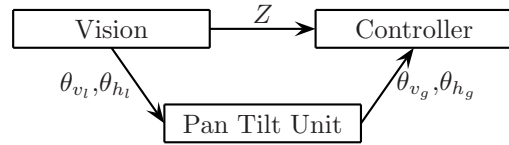


Figure 2: Processes and Communication model

1024x768 bit depth.

The majority of the reviewed techniques for vehicle and object detection are too computationally expensive for our purposes. The leader is uniquely identified by its colour feature; we secured a pink ball upon the robot. The pink hue is crucial since this is not a commonly occurring colour in the environment. This simplifies the problem of recognition, which can be achieved with a thresholding algorithm, this is presented in Algorithm 1.

Algorithm 1 Ball Recognition

loop

 Resample (1024x768 to 320x240)

 RGB to HSV conversion

 Hue and Saturation thresholding

 Hue \wedge Saturation

 Erode image

 Calculate centroids of balls

 Calculate disparity of balls' centroids

 Calculate distance to ball

end loop

The HSV colour space extracts the hue to a single component. We discovered that the pink ball had a very distinct saturation and so extracted this additional component. Doing this also further reduced the effects of surface reflections on the ball. We used OpenCV for all morphological operations. A logical conjunction of the two thresholded, binary images results in an image with a large blob representing the ball and occasionally speckles of noise. Erosion removes outer pixels from sets of adjacent pixels that match a structuring element. This is used to remove small clusters of pixels, assumed to be noise, from the image. We now have a binary image that represents the ball in the scene for each lens.

The centroid of the ball is taken for both images to produce 2D coordinates of the ball in images of the scene. Using the focal length (f) and baseline (T) of the pre-calibrated stereo vision camera and the calculated disparity from the two images (x_l, x_r) we triangulate the depth

of the ball (z) in the 3D environment as

$$z = f \frac{T}{x_l - x_r} \quad (1)$$

We only reconstruct the centre point of the ball in the 3D environment. The depth is then used to calculate the X and Y coordinates. The inverse tangent function is used to calculate the horizontal and vertical angles of the balls location so that the PTU can use these rotational units for actuations. With several optimisation techniques of our algorithm a frame rate of 7fps was achieved.

Strong, bright sunlight shining directly into the camera's lenses can cause the object recognition component to fail due to a large patch of illuminance which reduces the hue and saturation.

2.2 Object Tracking with PTU

A Pan Tilt Unit (PTU) tracks the leader and prevents it from leaving the camera's field of view. This is controlled with horizontal and vertical actuations of the PTU. We aim to maintain the pink ball's location's in the centre of the images to reduce the effects of radial distortion, which occur nearer to the perimeter of the images. This process acts as an intermediate for calculating the leader's location.

The PTU process receives horizontal and vertical angles of the ball's pose relative to the epip-centre of the camera's lenses. A proportional controller produces PTU commands to move the PTU. The local angles of the ball are then transformed to global angles that describe the ball's pose relative to the mount point of the camera on the robot. This is a global position of the ball which is passed to the controller process via shared memory.

2.3 Fuzzy Controllers for Speed and Direction

We can now recognise the leader, locate its position and track it in a 3D environment, we now discuss the robot's navigation system.

In order to maintain a safe distance between the leader and follower the speed of the follower is controlled. The heading of the follower will also change so that it follows the leader's path. This is essential since the robots are to traverse around corners.

Fuzzy logic controllers are used where there is much uncertainty and imprecision present. We operate in an unstructured environment and

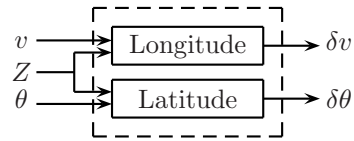


Figure 3: Fuzzy logic controller architecture

take measurements using a camera that inherently carry imprecision through pixel resolution. The kinematic model of skid steering over varying terrain possesses a huge problem which is partially overcome by the use of fuzzy logic control. Furthermore, the fuzzy sets that represent the control actions are intuitive to that of a human operator. We aim to operate this system in hard real-time and so more complex localisation, additional mapping and planning techniques are omitted to reduce computational complexity.

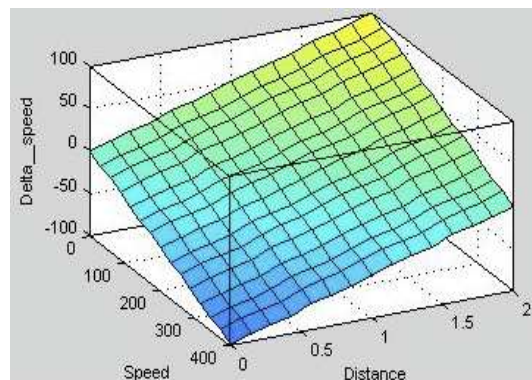


Figure 4: Longitudinal control surface

Actuator control is split into lateral and longitudinal(ACC) subsystems to simplify the relationship between the two, Figure 3 depicts the architecture. The Mamdani inference model is used because the outputs are known a priori, in fact the consequent sets model the desired output extremely well e.g. slow down a little. Both controllers have multiple input and single output architectures that are isolated from each other. The longitudinal controller's inputs are the current speed of the follower, v , and the distance to the leader, Z , while the output is a change in speed, δv . The lateral controller's inputs are the direction of the leader, θ , and the speed of the follower while the output is a change in heading $\delta\theta$. We define normal speed as 0.3ms^{-1} and a safe distance as 1m, these act as the set points. The universe of discourse for the distance between leader and follower ranges from 0m to 2m and the universe of discourse for the direction

of the leader relative to the follower ranges from -90° to 90° .

Exemplification [6] is used to determine the membership functions from our own experience and heuristic knowledge of driving vehicles and the robots. Both controllers have 5 membership functions per input and 9 output membership functions that are all triangular. With further use of our experience and knowledge we were able to determine the control rules. The control surface was visualised to ensure its smoothness, see Figures 4 and 5. A total of 25 rules accommodate for all scenarios that are encountered. The controllers were manually tuned.

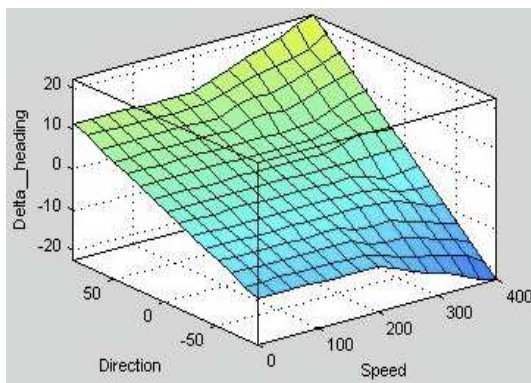


Figure 5: Latitudinal control surface

The minimum t-norm is used for intersection and the maximum t-conorm is used for the aggregation of the fuzzy sets. Larsen's product is chosen for implication operations for its ability to produce smooth control surfaces and its popularity amongst engineers and control applications [9]. For rule aggregation the maximum t-conorm is used and the centre of area method performs defuzzification.

The fuzzy sets are implemented as discrete data sets and integrated into the robot's API, Aria. An inference is performed for each controller every 100ms.

3 Experimentation

For evaluating the performance of the system our objective is to illustrate through comparative analysis a statistically significant difference between two types of fuzzy logic controller. The experimental methodology is presented here. We have a type-1 fuzzy controller and propose to implement a non-stationary fuzzy set controller. This was not done during this work but is discussed in section 6 as future research.

A SICK laser rangefinder mounted back-

wards on the leader collects distance measurements between the two robots, Figure 1 depicts the setup. This facilitates the ability to measure the accuracy of the system which is computable and also more accurate than the stereo vision camera. It records the distance to the base of the PTU on the follower. To achieve consistency between runs a track was drawn on a tarmac surface, see Figure 6 for the plan, that has varying degrees of corner, points T1, T2 and T3.

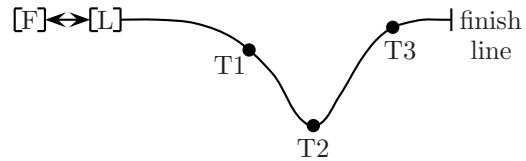


Figure 6: Plan of track with robots (F and L) and turns (T1, T2 and T3)

A human operator teleoperates the leader with a joystick and throttle button so that the middle of the robot is aligned with the track. Consistency and repeatability cannot be guaranteed with a human operator and so a 10m straight line starts the track to assess the follower's straight line performance. Measurements are recorded from the laser rangefinder and stored on the hard drive for parsing. This data is parsed offline to determine the root mean square error (RMSE) of a sample's variation from the set point of 1m. The experiments were conducted outdoors over two bright summer's days.

4 Preliminary Results

Figure 7 depicts a sample of the results recorded from the laser rangefinder. The first 150 measurements show good performance of the controller by maintaining a constant distance. Thereafter, the performance degrades. The peak just below the 400th measurement shows the largest amount of error, which reduces rapidly towards 0. This pattern was consistent with all runs, it is caused by the follower cutting a corner. Turn T2, see Figure 6, is the tightest turn that the follower cuts across. Various sources of error can be introduced into the experiment: consistency of leader's path, controller start, vision (finite resolution of images, defocusing, radial distortion), vibrations caused by skid steering on firm surface.

Figure 8 shows a plotted histogram of the preliminary results. This shows that the samples have a non normal distribution which implies

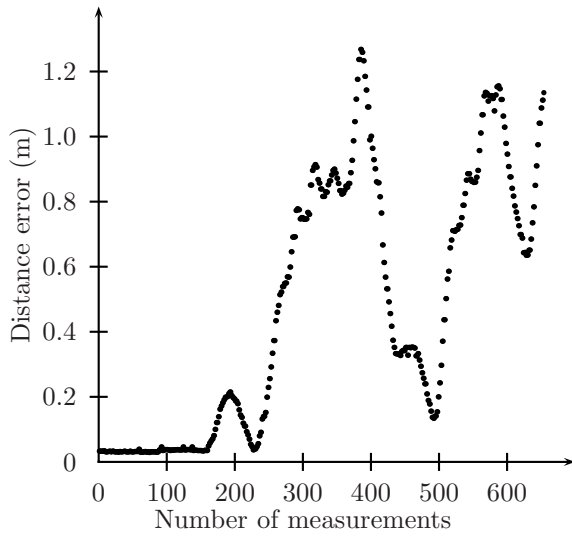


Figure 7: A single run

that a comparative analysis of nonparametric statistics would be suitable. Appropriate tests for this would be the Mann-Whitney-Wilcoxon and Kruskal-Wallis tests.

5 Conclusions

In this paper a control system is presented for following vehicles that integrates a stereo vision camera and fuzzy logic controllers for operation in an unstructured environment. The follower successfully recognised the leader and followed it to demonstrate the concept of vehicle following and ACC along a track. Although, the preliminary results suggest the performance is not yet consistent or reliable enough for comparative analysis we have proposed a framework for future research.

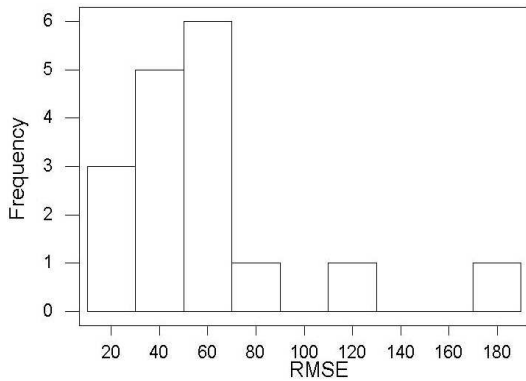


Figure 8: Histogram of samples

The vehicle recognition process worked well

in an unstructured environment, albeit the occasional interference from light sources. The follower's straight line performance of maintaining a constant distance is good. Difficulty was experienced when traversing through turns especially tight turns which often caused the follower to cut across the corner which suggests reconsidering the track design or the navigation method.

6 Future Research

Enhancing the accuracy, reliability and robustness of the vision and controller sub-systems is required for further use as a tool for data collection. A more accurate camera model, that considers radial distortion, and improved techniques for reliable and unique identification of the ball will increase the accuracy of localising the leader. Refining the controllers is crucial, either by employing an online or offline training method for the design that uses free motion to map the controllers' output to the real behaviour and an extension to this would be optimising the controller. A way point method of navigation could be utilised to consider situations where tight corners are encountered. This would coincide with our next point, the design of the track and experiments.

Our experimentation methodology is a key area for further development since there is much scope for experimental error. Teleoperating the leader produces inconsistent and unrepeatable control, so to prevail against this we propose (visual) servoing of the track.

Finally, for comparative analysis of our system we propose to create a non stationary fuzzy set controller. Non stationary fuzzy sets attempt to model the variation of human decisions [15]. This is achieved by perturbing the membership functions and aggregating many inferences. This presents an interesting area for future research especially for creating a method for inferring the fuzzy sets and perturbation parameters. It is envisaged that prior experiments would capture an operator's teleoperated control of a robot which would then infer the perturbation function.

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