Advances in Shared Discrete Event Control of the Robotic Cane

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Abstract

The Robotic Cane is an electronic travel aid for the visually impaired. The device is a wheeled platform, equipped with three ultrasonic sensors, which autonomously steers around obstacles. It is pushed by the user and to avoid obstacles the user has to simply walk behind it. However, the cane's control system does not know what the user wants to do. Therefore, user interactions are integrated into the shared control system. This paper improves on a previously presented control strategy which only utilised "distance to obstacle" data to determine the steering action. Presented here are three new control strategies to determine the steering action of the cane. The first strategy is based on the cane's velocity and the second on sensor confidence. The third method is based on a combination of velocity and sensor confidence.

1 Introduction

Assistive devices for people who have impairments such as disability, old age or the loss of one or more senses can greatly improve their quality of life. Such a device is the Robotic Cane presented in [Aigner and McCarragher, 1998b] and is shown in Figure 1. The Robotic Cane is an Electronic Travel Aid (ETA) for the visually impaired. The cane aids the user in navigating in everyday environments. A similar device is the GuideCane [Borenstein and Ulrich, 1997]. With the Robotic Cane the human is responsible for the high level control of the system, such as route planning, whereas the machine takes over more localised control, such as obstacle avoidance or wall following [Bell *et al.*, 1994]. The combination of the localised control and planning form a need for a shared control system.

The primary function of the Robotic Cane is to help the user avoid obstacles. Therefore this avoidance behaviour becomes the localised task and is the job of the autonomous control system. Many obstacle avoidance strategies exist for mobile robots. These include the vector field histogram method [Borenstein and Koren, 1991] applied to ultrasonic obstacle avoidance in the Guidecane and the Navchair [Bell *et al.*, 1993]. However, few navigation techniques take into account the dynamics of a mobile robot. [Austin and McCarragher, 1997] presents work in which a discrete event controller is utilised to steer a mobile robot through a corridor while keeping track of the approach speed to walls. However the entire environment is modelled as opposed to relative position to obstacles. Relative position is the approach utilised in this paper.

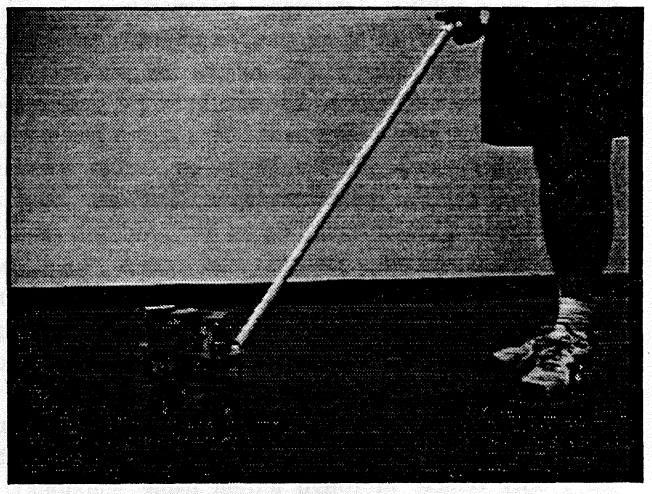

Figure 1: A walk with the Robotic Cane

For the Robotic Cane a shared discrete event control system is used [Aigner and McCarragher, 1998a] [Aigner and McCarragher, 1996]. The original control system of the robotic cane presented in [Aigner and McCarragher, 1998b] utilises only the distance to obstacles and human interaction to determine the steering command of the Robotic Cane. To improve the obstacle avoidance capabilities of the cane, monitoring techniques utilising the proximity of obstacles, cane velocity, sensor confidence and human interaction are investigated. These techniques allow thecane to take avoidance measures ear-

lier if travelling at higher speeds or later if the human so desires. Experiments are included to demonstrate the results.

2 The Cane and Control System

The Robotic Cane is a light, wheeled platform with a long handle so that it can be comfortably pushed in front of the user while walking. The cane steers around obstacles which are sensed with three ultrasonic distance sensors. Therefore, to avoid obstacles, the user simply has to follow the cane's path. Two independently steerable wheels allow the wheels to act as a brake if needed. The Robotic Cane is also equipped with two odometers from which speed can be determined. Further details can be found in [Aigner and McCarragher, 1998b].

The Robotic Cane uses a shared discrete event controller to make steering decisions [Aigner and McCarragher, 1996]. This control system is made up of four sub-systems. Without human interaction, control commands are provided by the Autonomous Discrete Event System (ADES). The user interacts through the Human Discrete Event System (HDES) sub-system. The third sub-system is the cane itself with its sensors and actuators. Finally an interface enables communication between the above three sub-systems.

To control the cane according to the distance relative to obstacles its equations of motion must be determined. Figure 2 shows a reference frame, [x y], attached to the

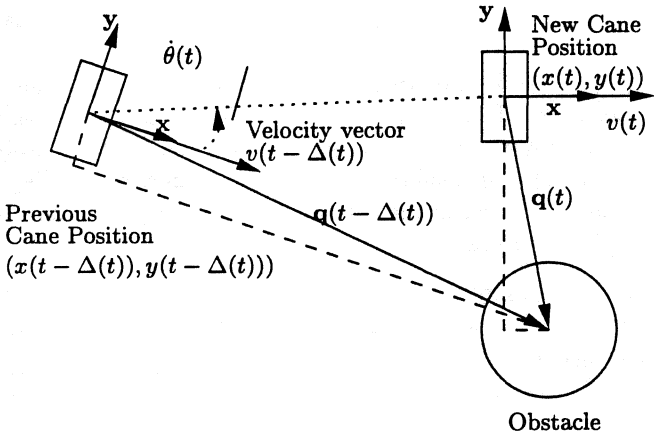

Figure 2: Equations of motion

cane. Note that the cane always travels in the x direction. The equations of motion can be expressed as

$$\dot{\mathbf{q}}_i(t) = \begin{bmatrix} v(t) - y(t-\Delta t)\dot{\theta}(t) \\ (v(t)t + x(t-\Delta t))\dot{\theta}(t) \end{bmatrix} \quad (1)$$

where $\dot{\mathbf{q}}_i(t)$ is the change in the distance to an obstacle at time t ($1 \leq i \leq 3$ refers to one of the three sensors), $v(t)$ is the speed with which the human is pushing (always in the x direction and determined by wheel encoder readings), $\dot{\theta}(t)$ is the change in the input command and therefore the new direction of travel, Δt the time between sensor samples and $(x(t), y(t))$ is the measured position of an obstacle relative to the cane at time t. Note that the accuracy of $(x(t), y(t))$ is only as accurate as the sensors and that each sensor can sense only one obstacle at one time.

The ADES controls the autonomous obstacle avoidance behaviour of the cane. The ADES is modelled as a finite state machine which is event driven. This finite state machine models possible conditions associated with the three sensors. An inequality associated with each sensor is true if the cane is far enough from an obstacle otherwise the inequality is false (see Section 3). Therefore each of the three inequalities represents whether or not the path in front of a sensor is clear. With three inequalities which are either true or false the ADES has eight states, γ_1 to γ_8. Any change in the inequalities constitutes an event and therefore causes a change in the ADES state.

Via the HDES, the human user can issue four commands to change the behaviour of the cane. He can make the cane go straight, turn left, turn right or issue the approach command. The approach command allows the cane to approach obstacles closer than it normally would under autonomous control. These four commands are all discrete interactions and are modelled in a hierarchical manner in the HDES. A general model of the HDES was developed in [Aigner and McCarragher, 1996] [Aigner and McCarragher, 1998a]. The user can issue these commands using a joystick mounted on the handle of the cane.

The fourth component, the Interface, provides a mapping from ADES and HDES commands to the turning angle of the cane. This mapping, ϕ, determines the turning angle, $\theta(t)$, based on the control command from the ADES the HDES. In this case, a lookup table, shown in Table 1, defines the control mapping. The mapping is established according to what a natural course of action would be. An example of this is a left turn if there is an obstacle on the right.

3 Process Monitoring

To determine if an event has occurred a process monitor, ψ, is utilised. In this paper three different types of process monitors are presented and tested. The first is based on velocities relative to potential obstacles. The inclusion of velocity has the advantage that braking distances are incorporated. The second method utilises sensor con-

ADES Command	*HDES Command*	*Combined Control*
Straight	Left	Straight
	Right	Left
	Straight	Right
		Straight
Light Left	Left	Light Left
	Right	Left
	Straight	Right
		Brake & Left
Stop	Left	Stop
	Right	Left
	Straight	Right
		Straight
Left	Left	Left
	Right	Left
	Straight	Right
		Straight
Light Right	Left	Light Right
	Right	Left
	Straight	Right
		Brake & Right
Straight	Left	Straight
	Right	Left
	Straight	Right
		Straight
Right	Right	Right
	Left	Left
	Right	Right
	Straight	Straight
Stop	Left	Stop
	Right	Left
	Straight	Right
		Straight

Table 1: Control mapping, ϕ, from ADES and HDES commands to combined cane control command

fidence. Sensor confidence is a measure of how often the sensors change given a stationary platform. If the sensor reading changes often then it can be said that the sensors are not reliable and hence sensor confidence is low. Greater caution is therefore required. The third process monitor combines speed measurements and sensor confidence to make the system more reliable than with either method alone.

The general inequality which determines if an obstacle is too close is given as

$$|\dot{\mathbf{q}}_i(t)|^2 - 2a_{max}\eta(t)k_1|\mathbf{q}_i(t)| \leq 0 \qquad (2)$$

where the index $1 \leq i \leq 3$ and refers to one of the three sensors, a_{max} is the maximum deceleration of the system, $\eta(t)$ is the confidence parameter and k_1 is a scaling constant.

For the first method utilising velocity only, consider the cane heading toward an obstacle, action to avoid the obstacle must be taken sooner if the cane is travelling fast. This gives rise to a restriction based on the velocity perpendicular to the obstacle and the distance from the obstacle. For this method, the term $\eta(t)k_1 = 1$ in inequality (2).

Sensor confidence can also be used in determining when the system needs to react. In a system in which sensors are inaccurate or give conflicting readings sensor confidence can give a good measure of when the system needs to be more conservative. For example, if sensors readings change by large amounts between samples the confidence in the sensors may be low. In this situation the system must be constrained earlier because "trust" in sensors is low.

Let the confidence parameter, $\eta(t)$, vary up and down depending on the recorded sensor data. This confidence parameter increases if the sensors give the same result with each sensor scan and decreases otherwise. Not only does the sensor confidence help if poor sensors are employed, it has an additional effect in cluttered environments. In cluttered environments the sensors change regularly as different obstacles are detected. Therefore the control system becomes more "cautious" and obstacle detection events occur further from obstacles.

The confidence parameter has limits of $1.0 < \eta(t) < 100.0$ and its level increases and decreases according to

$$\eta(t) = \eta(t-\Delta t) + \begin{cases} +0.5\Delta t \; if \; sens(t) = sens(t-\Delta t) \\ -1.0\Delta t \; if \; sens(t) \neq sens(t-\Delta t) \end{cases} \qquad (3)$$

where Δt is the time interval between sensor scans in seconds. The confidence falls twice as fast as it rises. This difference in rate was determined to be suitable from experimental results. It has the effect that once the cane is not confident it takes longer to regain confidence in the sensors.

Let us assume that in inequality (2) the velocity term, $|\dot{\mathbf{q}}_i(t)|^2$, is constant. Inequality (2) can now be written as $\eta(t)|\mathbf{q}_i(t)| - k_2 \geq 0$, where k_2 is a new constant. This is the inequality which determines events based on confidence.

Sensor confidence alone can sometimes be misleading in providing a means of activating constraints. If sensor bandwidth is low but the environment is changing rapidly the confidence can remain high as sensors are not changing quickly enough. In this case avoidance action may be taken too late thus causing a potentially dangerous situation. The combination of sensor confidence with another method is thus logical. In this case velocity monitoring is considered in conjunction with sensor con-

fidence to improve the performance over either method on its own. Inequality (2) combines the two methods without further modification.

4 Experiments

Experiments were conducted to test the operation of the three process monitoring methods described.

4.1 Velocity Monitoring

The velocity monitoring was implemented using equation (2) with $\eta(t)k_1 = 1$. Figures 3 and 4 show two experiments with velocity monitoring only. The user did not interact and thus the HDES state remained in the No Interaction state, throughout the experiment. The a_{max} parameter from Equation (2) was set to $2.0m/s^2$.

Figure 3 shows operation with a fast approach speed. On the figure the length of each line segment represents the speed with which the cane was travelling. State transitions or events in the ADES are indicated by Δ labels. It can be seen from the figure that an event occurred approx. 2m from the wall (inequality 3 associated with the left most sensor became false) with a speed of approx. 3m/s. This event caused the ADES to change state and the cane then executed a right turn. The additional state transitions are due to the middle sensor also receiving an echo from the wall.

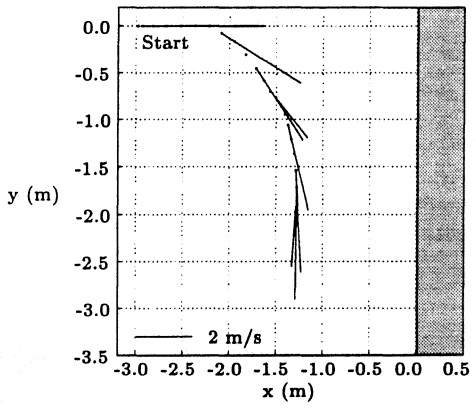

Figure 3: Path of cane with a high speed approach

Figure 4 shows the above experiment repeated with a slow approach speed towards the wall. The speed here was approx. 0.8m/s. It can be seen that the cane did not turn away until 0.5m from the wall. In this case only inequality 3 (left sensor) became false.

It is shown that the cane turned further from the wall at higher speeds. A disadvantage of this method comes about from reacting to obstacles further away and the sensors being less accurate at longer distances. This means that sensing errors increase and hence incorrect control commands can become more frequent.

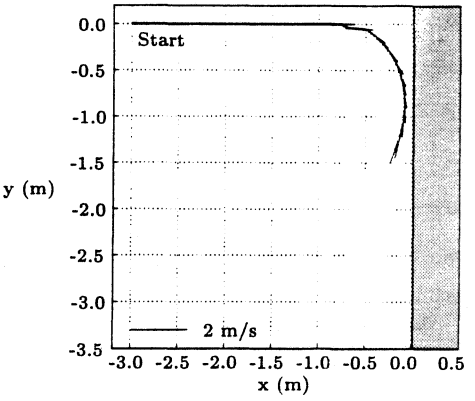

Figure 4: Path of cane with a low speed approach

4.2 Sensor Confidence Monitoring

Experiments were conducted to test the monitoring utilising sensor confidence. The constant, k_2, in the modified inequality for confidence monitoring was set to 30.0. This value causes the inequalities to be false at distances less than 0.3m even at maximum confidence. Therefore the cane will not get closer than than 0.3m to an obstacle without turning or stopping.

The first experiment is shown in Figure 5. The value of the confidence parameter is shown as the length of the line segments. The cane approached the wall with a confidence of approximately 1.0. Inequalities 2 and 3 becomes false at approx. 2.0m from the wall. This causes an event and the cane thus turns away from the wall.

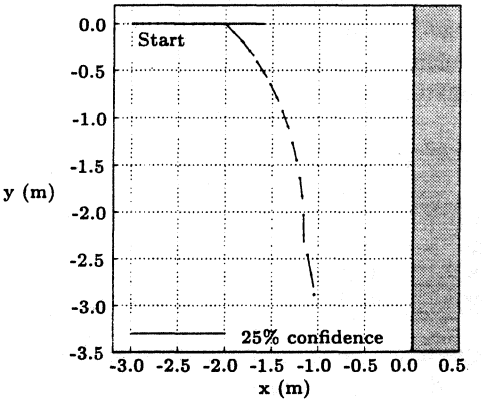

Figure 5: Path of cane with low confidence

In contrast Figure 6 shows the cane approaching the wall with a confidence of 100.0 at the start. The confidence drops as soon as the sensors pick up the changes in the distance from the wall. An event occurs when sensor 3 causes its inequality to become false at a distance of 1.2m from the wall with a confidence of approx. 20.0. Soon after this event, inequality 2 becomes false, triggering another event.

The sensor confidence operates well in environments

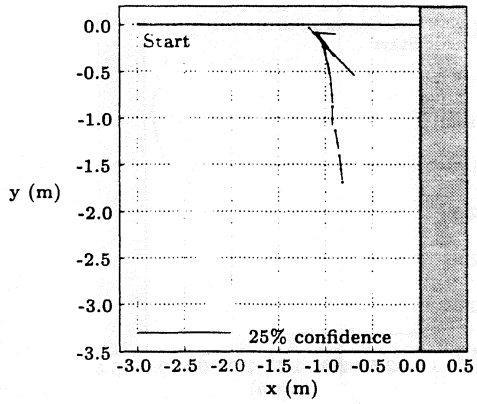

Figure 6: Path of cane with high confidence

with few obstacles because the confidence rises between obstacles. However, in cluttered environments the confidence tends to remain low. Therefore the cane will turn away from obstacles sooner. This reduces the space to move dramatically and becomes a control strategy which is too restrictive. Particularly in indoor environments where distances between obstacles (walls, doors, furniture and fittings) is rarely greater than 4m.

4.3 Combined Velocity and Sensor Confidence

To overcome shortcomings of each method alone, the combination of velocity and sensor confidence for process monitoring was tested. Four experiments were conducted, each showing one of the four extremes possible. During this set of experiments the scaling constant (2), k_1 was set such that $2.0 < a_{max} * \eta(t) * k_1 < 6.0$. The four experiments and their outcomes are summarised in Table 2.

Speed (m/s)	Confidence (score)	Turned at (m)	Expected range	Fig.
~ 4.0 (high)	~ 7 (low)	~ 2.8	furthest	7
~ 3.5 (high)	~ 70 (high)	~ 2.0	far	8
~ 1.2 (low)	~ 6 (low)	~ 1.0	close	9
~ 1.8 (low)	~ 50 (high)	~ 0.7	closest	10

Table2: Experiments conducted with combined velocity and sensor confidence constraints

In the first experiment with high velocity and low confidence the expected outcome is that the cane is extra "cautious". Therefore we expect the cane to turn away from the wall early. This experiment is shown in Figure 7. The wall is approached and it can be seen that an event occurs at the point at which recording started ("Start" on the graph). This event caused the cane to turn away. First the leftmost sensor senses an obstacle such that inequality 3 becomes false. Shortly thereafter the middle sensor also triggered an event and the cane turned away early.

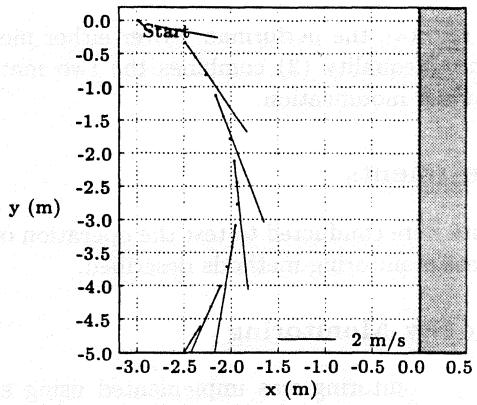

Figure 7: Combined constraints: high velocity low confidence

With high velocity and high confidence (Figure 8) the cane turned at 2m from the wall, closer than the previous experiment. This is because the higher confidence (as opposed to low confidence previously) allows the cane to get closer to obstacles. When the turn was initiated both, inequalities 2 and 3 become false. Inequality 2 becomes true shortly thereafter. At the end of the travelled path, the ADES state changes back to the "No Obstacle". Here the cane was parallel to the wall and no obstacles were detected.

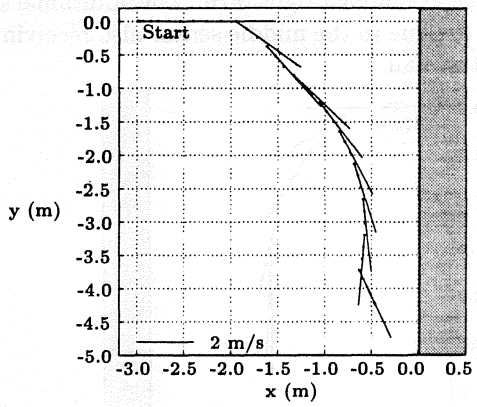

Figure 8: Combined constraints: high velocity high confidence

The third experiment had low velocity and low confidence. The low velocity normally allows the cane to get closer to walls. However the low confidence causes the cane to turn earlier than it would with a high confidence. This experiment is shown in Figure 9. Here the cane turned at a distance of approximately 1.0m.

In the final experiment with the combined method the cane turned away at a distance of only 0.7m. This distance is the lowest. It is achieved with a high confidence and a low velocity. Both, the low velocity and high confidence allow the cane to get close to an obstacle. This is shown in Figure 10.

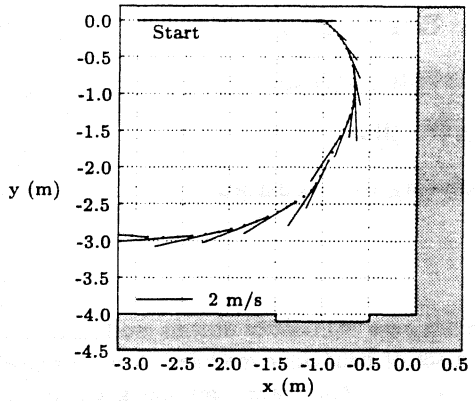

Figure 9: Combined constraints: low velocity low confidence

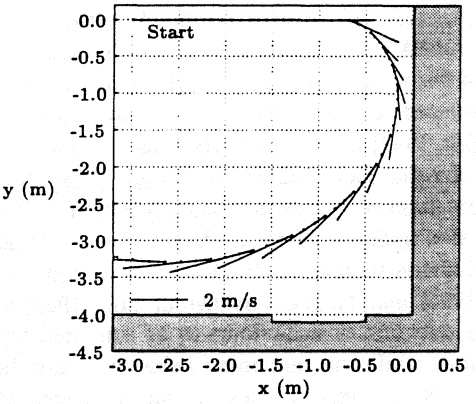

Figure 10: Combined constraints: low velocity high confidence

The results indicate that the method of combining velocity and sensor confidence is a alternative method for performing process monitoring. The combined method also overcomes the disadvantage of sensor error of velocity sensing at longer distances as the confidence method is better at longer distances. At shorter distances where the confidence alone performs poorly, the velocity method helps. Therefore the combination adds a further degree of robustness to the control of the cane.

5 Conclusion

The paper demonstrates how three different monitoring techniques are used to effectively control a robotic aid for the visually impaired. The process monitoring was integrated with a shared discrete event controller to allow for user interaction as well autonomous operation.

The results show that monitoring based on velocity works quite well on its own. However, the velocity method presents a design tradeoff at high speeds because the larger, less accurate, distance measurements become more significant.

The confidence method alone also worked in avoiding obstacles. However, in environments which are changing regularly or are cluttered, the confidence remains low. For this reason the cane will often steer away earlier than is often necessary thus reducing the available space.

The cane performed well, operating at high velocity with high confidence parameters. The advantage of this method is that it overcame the difficulties associated with the velocity or confidence methods on their own. However, with high speed and low confidence, (Figure 7), the cane tends to steer away from obstacles far sooner than what is necessary. In the example presented, the turn is initiated 2.8m from the wall.

Future improvements of the cane include further work on the shared control aspects. This includes the "Approach" command which will enable the user to get closer to obstacles. Generally the cane is an easy to use device which provides an alternative to the commonly used white cane.

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