Multi-Agent Autonomous Pilot for Motorcycles

Dana Vrajitoru
Intelligent Systems Laboratory
Indiana University South Bend
Computer and Information Sciences Department
e-mail: danav@cs.iusb.edu

Russel Mehler
Intelligent Systems Laboratory
Indiana University South Bend
Computer and Information Sciences Department
e-mail: rmehler@iusb.edu

Abstract

In this paper we introduce a visualization application for a vehicle simulation with an automatic pilot. The application is written in OpenGL and includes a model of a vehicle (a motorcycle) based on the physical laws of motion, including kinematics, gravitation, and friction. The vehicle can be controlled by the user through keyboard and mouse commands, as well as by an automatic pilot. The latter is implemented as a multi-agent probabilistic scheme using perceptual data. Our intention is to simulate the behavior of a human driver on the road. The performance of the automatic pilot is compared with that of a human player.

Introduction

The autonomous pilots are an important aspect of developing the vehicles of the future and they represent an interesting challenge for intelligent control applications as well as for traffic control (Kelly 1997; Mourant & Refsland 2003). This project starts from a simulation of a vehicle with a multi-agent autonomous pilot using perceptual information. The application aims to control the vehicle in a non-deterministic way inspired from the behavior of a human driver and using the same kind of perceptual information to make decisions.

In this paper we introduce a simulation of a vehicle with a multi-agent autonomous pilot using perceptual information. The goal of this application is not to develop a pilot capable of driving the vehicle in a stable and deterministic way, but to simulate the behavior of a human driver under various circumstances on the road.

The intelligent agents represents a modern approach in artificial intelligence and they have been extensively utilized for many applications (Weiss 2000; Wooldridge 2002). Several approaches have applied multi-agent models to the simulation of autonomous drivers (Al-Shihabi & Mourant 2003; Sukthankar, Baluja, & Hancock 1998) and our application follows similar ideas. A related research direction focuses on traffic flow simulation (Nagel 1996; Kelly 1997) or trajectory planning (Atkins *et al.* 1998).

Most of the research on autonomous pilots is directed toward piloting aircrafts (Martinos *et al.* 2003; Mot & Feron 2003; Abdelzaher, Atkins, & Shin 2000; Gavrilets *et al.* 2001), and cars (Mourant & Marangos 2003). Our approach targets motorcycles which have not yet been studied as extensively as the other types of vehicles and which represent a more challenging modeling problem.

The application we are presenting in this paper is developed using the ideas and concepts that can be observed in game engines. It is implemented using the OpenGL library and provides real-time interaction for a human player. The visual interface of the application allows the human user to adjust the point of view and to drive the vehicle, which in our case is a motorcycle. The application includes an autonomous pilot that can be toggled on and off as well as a test circuit that the human or automatic driver must attempt to complete.

The automatic pilot is a multi-agent probabilistic application with a separate configuration interface where each agent is an independent process acting on one of the control units of the vehicle, as for example, the gas, the brakes, the handlebars, or the steering wheel. The agents use some information about the current status of the vehicle to make a decision about an action to be taken on their respective control units. This information includes both status data, like the current speed, and perceptual data, as the visible distance on the road in the direction of movement, the lateral distance to the border of the road, and the current slope. The performance of the automatic pilot is compared with the performance of a trained human.

The paper is structured the following way. Section describes the physical model and the equations that we have used in our simulation. Section introduces our multi-agent automatic pilot. Section presents the GUI and other implementation details for our application. Section presents some results of our simulation and compares them with the performance of a human player. We finish the paper with some conclusions.

Physical model

In this section we introduce the physical equations that we have used to simulate the vehicle and to control its behavior. Most of the equations modeling the motorcycle can be found in (Bourg 2002) and (Anderson 2001).

The Equations of Motion

Let us consider the following notations:

- $s(t)$ the spacial position of the object at time t,
- $v(t)$ the momentary speed or velocity, $v(t) = s'(t)$,
- $a(t)$ the momentary acceleration, $a(t) = v'(t) = s''(t)$.

By applying Taylor's equation, we can derive the following system of equations defining the spacial position of the motorcycle at the moment $t + \Delta t$:

$$\begin{aligned} s(t+\Delta t) &= s(t) + v(t)\cdot\Delta t + a(t)\tfrac{\Delta t^2}{2} \\ v(t+\Delta t) &= v(t) + a(t)\cdot\Delta t \end{aligned} \tag{1}$$

In our case, the acceleration is defined by the amount of gas supplied to the engine by the throttle, by the force applied to the brakes, by the friction force, and by the gravitational force. The system is set in such a way that a given amount of gas supplied to the engine can only lead to accelerating the vehicle up to a speed limit depending on the amount of gas. This simulates the engine limitations of a real vehicle. Let us denote by $sl(s(t))$ the angle made by a tangent to the road in the direction of movement with the horizontal plane. The following equation is used to determine the acceleration applied to the vehicle:

$$a(t) = throttle(t) + eb\, g\, \sin sl(s(t)) - k\, g\, \cos sl(s(t)) \tag{2}$$

In this equation, the first term represents the amount of gas supplied to the engine, the second one the amount of gravitation applied to the vehicle in the direction of movement, depending on the gravitational acceleration on the surface of the Earth, $g = 9.8\ m/s^2$, and on the slope of the road at the current point in space in the direction of movement. The last term represents the acceleration generated by the friction force, depending on a constant specific to the surface material, k, and on the gravitational acceleration normal to the surface, which is equal to g multiplied by the cosine of the slope angle. From this equation we also substract an amount depending on the force applied to the brakes.

The amount of acceleration that applies to the vehicle from the gravitational source depends on the slope of the road. In the case of a motorized vehicle, we also need to consider that the engine is compensating for a big part of this acceleration, be it a percentage denoted by eb for engine brake. For example, we could have $eb = 0.95$, meaning that only 5% of the gravitational force will influence the movement of the vehicle.

The equations of the spacial position and of the speed becomes

$$\begin{aligned} s(t+\Delta t) &= s(t)+v(t)\cdot\Delta t+(a(t)+ga(t)\Delta t^2/2 \\ v(t+\Delta t) &= v(t)+(a(t)+ga(t)\cdot\Delta t \end{aligned} \tag{3}$$

The Handlebar

A special model is necessary to explain the behavior of the motorcycle when the lateral axis of the handlebar is not orthogonal to the central axis of the motorcycle.

Let $ha(t)$ be the angle made by the plane of the front wheel with the central plane of the motorcycle and let ds be the horizontal distance covered by the vehicle is the lapse of time Δt. We would like to determine the new angle between these two plane after Δt, $ha(t+\Delta t)$ and the new position $s(t+\Delta t)$.

To simplify the model, in our program we consider that if the distance ds is greater than the distance between the centers of the wheels, then the direction of movement is simply rotated by the angle $ha(t)$ and the new position is calculated by translating the vehicle by the distance ds in the new direction of movement. This idea is illustrated by Figure 1.

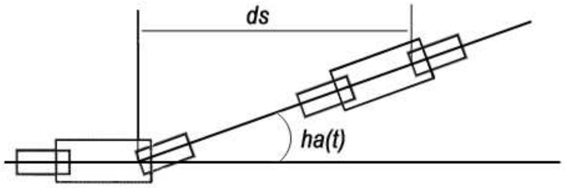


Figure 1: Change in direction due to the handlebar

In the case where the distance ds is smaller than the distance between the centers of the wheels, we determine the new direction of movement and the new orientation based on the idea that the front wheel will move in the direction that it is facing, which is given by the position of the handlebar. In our case the back wheel continues along the former direction of movement while gradually changing its orientation to match the orientation of the front wheel. This is a small simplification of what happens in the case of a real motorcycle. The new direction of movement is given by the straight line between the centers of the wheels. Figure 2 illustrates the interpretation we have adopted for the second case.

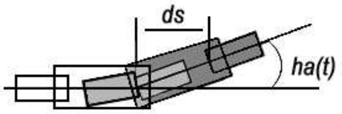


Figure 2: Change in direction due to the handlebar, short distance

With this model, if the distance ds is exactly equal to the distance between the wheel centers, the two wheels reach the same orientation in both situations, such that the movement is actually continuous.

Center of Mass

The center of gravity or center of mass is an important factor having a major role in the lateral movement of the vehicle. To model this unit, we must define the parts composing the motorcycle and the resulting center of mass based on their positions.

For an object with varying density, the center of mass is computed as an integral over its volume of the local mass multiplied by the position, and divided by the total mass. The equation has the following expression, where x_c is the position of the center of mass, m the total mass, $x(i)$ and $m(i)$ represent the location and the mass of a unit of volume respectively:

$$x_c = \frac{1}{m} \int_V x(i)\, m(i)\, di \tag{4}$$

In our case we will consider that the moving object is composed of several units, each of them having a well defined center of mass. The global center of mass is defined by the positions of all the composing units relative to each other. Let us consider k objects, each of them having the position x_i and the mass m_i, $i = 1, \ldots k$. Then the global center of mass is defined as

$$x_c = \frac{1}{\sum_{i=1}^{k} m_i} \sum_{i=1}^{k} m_i \cdot x_i \tag{5}$$

In our case, we consider the independent units of our object to be the following:

- the motorcycle itself
- each leg of the driver
- each arm of the driver
- the driver's torso
- the driver's head

These units are not entirely independent with respect to each other, and we must define the relative constraints of their movement. In this context they define the parts composing the moving object, each having a center of mass that can move with respect to each other.

Lateral movement

The first force that we are going to consider that affects the lateral movement of the vehicle is the *centrifuge force*. This force is defined by

$$F_c = m\, \omega^2\, r \tag{6}$$

where ω is the angular speed, and r is the radius of the circle on which the object is turning. If v is the horizontal speed, then we can define the angular speed as $\omega = v/r$, so the centrifuge force is equal to

$$F_c = m \frac{v^2}{r} \tag{7}$$

A second force that interacts with the vehicle in the lateral movement is the lift force due to the friction with the air. We can adapt an equation taken from airplane wing simulation that computes the *lifting force* F_L as

$$F_L = \frac{1}{2} \rho v^2 S_{ref} C_L \tag{8}$$

In this equation ρ is the air density, that we can consider to be approximately $\rho = 1.22145 kg/m^3$ at 0 altitude. S_{ref} is the reference area, that we can compute as the horizontal projection of the vehicle. If S_v is the total porting lateral surface of the motorcycle and the driver, S_h the porting horizontal surface of the motorcycle, and α is the angle made by the vertical axis of the motorcycle with the horizontal plane, then

$$S_{ref} = S_v \cos\alpha + S_h \sin\alpha \tag{9}$$

The last component of the lateral movement is the gravitational force itself, which has a norm equal to $g\,m$. From this force, we have to subtract the lifting force first. Starting from the same angle α, the resulting force which is vertical can be decomposed into a force oriented along the vertical axis of the motorcycle and another one that is orthogonal to the motorcycle. The rotation will be determined by the component that is perpendicular to the motorcycle axis. This component, that we call *central gravitation* and denote by G_c, is given by

$$G_c = (g\,m - F_L)\sin\alpha \tag{10}$$

By imposing the condition that the central gravitational force should be equal to the centrifuge force, we can compute the rotation radius r:

$$r = \frac{m\,v^2}{(g\,m - F_L)\sin\alpha} \tag{11}$$

All of the forces and quantities involved in the description of the lateral movement are illustrated in Figure 3.

The Autonomous Pilot

In this section we present the ideas that we have used to implement the autonomous pilot for our motorcycle.

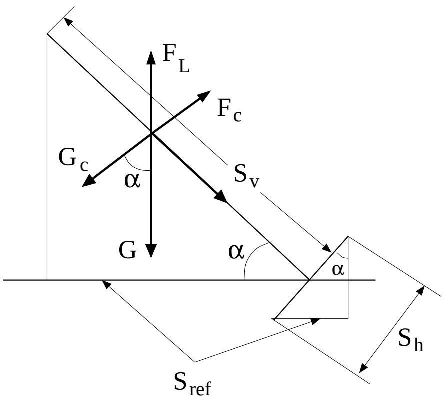


Figure 3: The forces and quantities involved in the lateral movement

Perceptual Information

The autonomous pilot is using perceptual information to make decisions about the vehicle driving. This information is inspired from the perceptual cues that a human driver would also be paying attention to while driving a vehicle.

In our application, the pilot is aware of the following measures:

The *visible front distance*, denoted by $frontd$, defined as the distance to the border of the road from the current position of the vehicle in the direction of driving. This distance is a measure of how much of the road is visible ahead and also of how straight the road is in front of the vehicle. Instead of the direct measure of this distance we a re going to use the quantity $front = frontd/length$ which is the proportion between the front distance and the length of the vehicle.

The *front probes*, denoted by $frontl$ and $frontr$, are defined as the distances to the border of the road from the current position of the vehicle following directions obtained by a rotation left and right of a small angle (1 degree in our case) from the direction of movement. The front probes can give the pilot an indication as to which way from the direction of movement the front distance would become larger, and eventually turn that way.

The *lateral distances*, denoted by $leftd$ and $rightd$, are measure of the lateral distance from the vehicle to the border of the road. We start by selecting a point in the direction of movement at a given distance ahead, as for example $2length$ (the length of the vehicle). From that point, we compute the intersections with the border of the road of a line which is orthogonal to the direction of movement. This represents an intuitive notion of how far the vehicle is from the lateral borders of the road as the driver is looking at some distance in front of them.

The *slope*, denoted by $slope$, is the slope of the road which determines the amount of gravitational acceleration that affects the vehicle in the direction of movement, and thus having an impact on the acceleration. The perceptual version of the slope used by the pilot is discretized to simulate the intuitive notion of road inclination that a human driver would have. Thus, the slope can have 5 discrete values, representing a road that is almost flat, that is slightly inclined up or down, and that is highly inclined up or down. We have chosen this representation of the slope to simulate the fact that a human driver would not be aware of the precise degree of inclination of the road, but would have a more general impression of this measure.

Figure 4 shows an example of the geometrical definition of these measures.

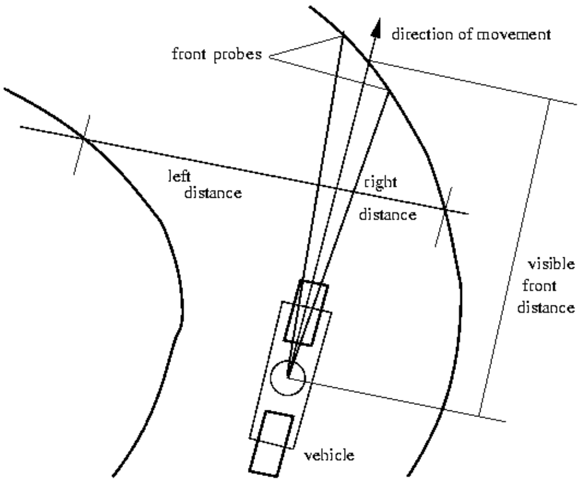


Figure 4: Perceptual information used by the autonomous pilot

Beside the perceptual information, the autonomous pilot is using the current status of the motorcycle to make decisions about the action to be taken on each of the control units of the vehicle. The status includes measures like the current speed, the current opening of the throttle, the brakes, and the current position of the handlebar relative to the direction of movement. The pilot can not directly change the speed, acceleration, and position of the vehicle, but instead it can perform some action on the control units that will eventually change the status of the vehicle the way we expect it to.

Control Units

The motorcycle is driven by several control units (CUs). Each of them is controlled by an independent agent with a probabilistic behavior. The agents are not active during the computation of each new frame simulating the evolution of the vehicle on the road, but only once in a while in a non-deterministic manner. This simulates the behavior or a human driver that may not be able to instantly adapt and take action based on the road situation and would require a certain reaction time.

The minimal model requires a CU for the gas - throttle, which determines the acceleration, for the brakes, which can slow down or even stop the vehicle, and for the handlebar that controls the direction.

Each of these control units is independently adjusted by an agent. The behavior of the agents depends on the status of the vehicle and is intended to drive the motorcycle safely in the middle of the road and at a speed as close as possible to a given limit. Each agent can have its own rate of interference with the coordination of the vehicle, and in our case, the agents controlling the throttle and the handlebar are in general more active than the agent controlling the brakes.

The next paragraphs introduce the equations used by each of our agents to make a decision and describing the action taken by the agents. The equations comprise a good number of constants, some of which are used by more than one agent with the same meaning. Even though these constants are the same in various equations, each agent has its own configuration values for them, which means that their behavior can be adjusted independently of other agents.

The Throttle

This CU and its corresponding agent controls the amount of gas that is supplied to the engine and determines the acceleration that the vehicle is submitted to.

This agent takes as input information the current speed, the front distance, the lateral distances, and the slope. The agent has three speed thresholds that it is using to adapt the amount of gas with the aim of adjusting the speed: a minimal threshold, that determines the minimal speed that the vehicle should have at any time; the maximal threshold, that represents the maximal speed at which the driver feels safe driving the vehicle, and the speed limit, which is an exterior measure that does not depend on the performance of the vehicle and of the driver.

The agent will attempt to keep the vehicle speed above the minimal threshold and below the maximal one, and also below the speed limit but not too different from it. If the lateral distance to the left is too far from the lateral distance to the right, the speed must be decreased because the road is most probably turning. The same rule applies to the visible distance in front of the driver: a short distance represents an unsafe road situation and the speed has to be decreased.

Let $tr(t)$ be the amount of gas going to the engine at the moment t, which in turn determines the acceleration of the vehicle. Let us also denote by lat_{norm} the normalized of the difference between the left and right distances as shown in Equation 12 and by $lat_{abs} = |lat_{norm}|$ the absolute value of this quantity.

$$lat_{norm} = \frac{leftd - rightd}{\max(leftd, rightd)} \tag{12}$$

Equation 13 presents the condition that must be fulfilled for the throttle to be increased or opened, which results in a higher acceleration followed by an incrementation of the speed. In this equation, v_{low} is a lower limit for the speed, thr_{lat} is a threshold under which we consider that the difference between the left and right distances is still safe, thr_{front} is the threshold for the safe front distance, v_{limit} is an upper speed limitation, like the legal speed limit on that road, and c_{tr} is a constant.

$$\begin{array}{rll} v(t) & < v_{low} & \text{or} \\ lat_{abs} & > thr_{lat} & \text{and} \\ front & > thr_{front} & \text{and} \\ v(t) & < v_{limit} & \text{and} \\ v(t) & < c_{tr} \cdot tr(t) & \end{array} \tag{13}$$

Let us denote by tr_{lat} a quantity indicating if the normalized absolute difference between the left and right distances is safe for the vehicle's current speed, as shown in Equation 14 where c_{vlat} and $pvlat$ are constants. For higher values of the speed, the safe difference is smaller.

$$tr_{lat} = lat_{abs} - \frac{c_{vlat}}{(1 + v(t))^{1/pvlat}} \tag{14}$$

Let us denote by tr_{fr} a quantity indicating if the front distance is safe for the vehicle's current speed, as shown in Equation 15 where c_{vfr} and $pvfr$ are constants.

$$tr_{fr} = \frac{c_{vfr}}{(1+v(t))^{1/pvfr}} - front \tag{15}$$

Equation 16 represents the condition to be fulfilled for the throttle to be decreased or closed, which will have the effect of slowing down the vehicle under the influence of the friction force.

$$v(t) > v_{limit} \text{ and } tr_{lat} > 0 \text{ and } tr_{fr} > 0 \tag{16}$$

Let us denote by $\Delta tr = tr(t+\Delta t) - tr(t)$. The equation governing the change in throttle that the agent will perform based on the current vehicle and road status is illustrated by Equation 17 where c_{incv}, c_{decv}, and c_{sl} are constants. The actual amount of the change is a probabilistic quantity equally distributed in a small neighborhood around the computed value.

$$\begin{aligned} \Delta tr = c_{incv}(front - thr_{front})(v(t) - v_{low}) + \\ c_{decv}\left((v(t) - v_{limit}) + tr_{lat} + tr_{fr}\right) + c_{sl} \cdot slope \end{aligned} \tag{17}$$

The Brakes

The agent controlling the brakes has a similar behavior to the one controlling the throttle because we have assumed that the rules deciding when the speed should decrease are of general purpose. The equations of this agent though are simpler because the brakes can only decrease the speed and not increase it. The speed can actually be reduced by decreasing the amount of gas received by the engine, in which case the friction with the ground would slow down the vehicle, but also by activating the brakes, which has a more direct effect on the speed and should be used when the necessary change in speed is bigger.

The criteria used by the agent in charge of the brakes to decide when to apply a force on the brakes, which would result in a more dramatic decrease of the acceleration and of the speed than decreasing the throttle, are the same as for the agent in charge of the throttle, and are specified by Equation 16. Given the fact that even though the two agents are using constants with the same name, those constants can have independent values for each of them, a decrease of the throttle does not necessarily mean an action on the brakes. The brakes are actually used less often than the throttle.

Let $br(t)$ be the amount of force applied to the brakes at the moment t. In general, this force is distributed 40% on the back brake and 60% on the front brake. Just as befores, let $\Delta br = br(t+\Delta t) - br(t)$. The brakes are handled by an agent with a probabilistic behavior based on Equation 18, which is very similar to equation 17, but the constants and thresholds present in this equation can be adjusted independently of the agent controlling the throttle, as stated before.

$$\Delta br = c_{decv}\left((v(t) - v_{limit}) + tr_{lat} + tr_{fr}\right) - c_{sl} \cdot slope \tag{18}$$

The Handlebar

A special agent is in control of the handlebar of the motorcycle, the equivalent of the steering wheel for a car. This agent is also using the lateral distances to the border of the road, as well as the front probes $frontl$ and $frontr$, to make decisions about turning the handlebar left or right. The agent turns the handlebar in the direction of the longer distance between the left and right, getting away from the closest border.

The agent starts by making a decision whether to use the lateral distances as reference or the front probes. Let us denote by $probe_{norm}$ the normalized of the difference between the front left and right probes as shown in Equation 19 and by $probe_{abs} = |probe_{norm}|$ the absolute value of this quantity.

$$probe_{norm} = \frac{frontl - frontd}{\max(frontld, frontd)} \tag{19}$$

Let us denote by lat_{diff} the quantity used by the agent to decide if it must turn and in which direction, computed according to Equation 20.

$$lat_{diff} = \begin{cases} lat_{norm} & \text{if} \quad lat_abs > thr_1 \text{ and} \\ & \quad frontd > thr_2 \\ \frac{lat_{norm}+probe_{norm}}{2} & \text{if} \quad lat_abs > thr_3 \text{ and} \\ & \quad frontd > thr_4 \\ probe_{norm} & \quad otherwise \end{cases} \tag{20}$$

The amount of the change depends on how different the left and right lateral distances are either right next to the vehicle or at the intersection with the road in front of it, based on the measure lat_{diff}, and on the speed. Thus, if the speed of the motorcycle is lower, the handlebar has to be turned more to achieve a given change in direction. If the vehicle moves at a higher speed, smaller changes in the orientation of the handlebar are necessary to obtain the same change in direction.

The handlebar agent will update the handlebar position if the condition expressed in Equation 21 is fulfilled. This means that a change is necessary either if the lateral difference measure is greater than the threshold thr_{lat}, or if the distance in the direction of movement to the border of the road is smaller than another threshold, thr_{front}.

$$|lat_{diff}| > thr_{lat} \text{ or } front < thr_{front} \tag{21}$$

If we denote $\Delta ha = ha(t+\Delta t) - ha(t)$, then the general rule for modifying the orientation of the handlebar is shown in Equation 22, but the actual amount of the change is a probabilistic quantity equally distributed in a small neighborhood around the computed value.

$$\Delta ha = c_{hbar} \left(lat_{diff} + \frac{thr_{front} - front}{thr_{front}} \right) \tag{22}$$

Alerting Agent

Beside all the agents that are in direct control of the motorcycle, the pilot comprises a fourth agent that does not perform any action on the vehicle. While the other agents are active only occasionally, this agent is probing the vehicle and road condition for every new frame and is capable of activating one of the other agents if the situation case requires special attention. Thus, if the speed of the vehicle is either too high or too low, or if the visible front distance is too short, or if the difference between the left and right lateral distances is too high, this agent considers the situation to be exceptional, meaning unsafe, and generates an alert event that will randomly activate one of the agents that can take action on the motorcycle and correct the issue.

Equation 23 describes the condition that must be true for the alerting agent to consider that the vehicle's status is not safe and one of the agents coordinating the vehicle must be triggered to take some action and correct the situation. The alerting agent only generates an alert message and does not decide which other agent will perform the necessary action.

$$\begin{array}{rcll} v(t) & < & c_{vlow} v_{limit} & \text{or} \\ v(t) & > & c_{vhigh} v_{limit} & \text{or} \\ lat_{abs} & < & thr_{lat} & \text{or} \\ front & < & thr_{front} & \end{array} \quad (23)$$

The Interface

The application's interface has two parts: the motorcycle visualization and the autonomous pilot configuration.

Motorcycle Visualization

This part of the application is represented by a graphical window implemented in C++ using the library OpenGL. The viewport is showing the motorcycle with the driver and is also displaying the test circuit.

The display is consistent with the status of the motorcycle and reacts in real-time to any changes in it. For example, the motorcycle's wheels are spinning at an angular speed derived from the horizontal speed of the vehicle. The handlebars are displayed at an angle with the central axis of the vehicle that reflects the actual driving angle.

The main loop of the application consists in computing the new status of the vehicle based on all of the equations introduced before, on the actions taken by the user, and on the actions taken by the autonomous pilot if the latter is active. The display is then updated based on the new status of all the objects composing the graphical scene.

The motorcycle can be controlled by the user through the usual keyboard commands, like the up and down arrow keys to accelerate and decelerate, the left and right arrow keys to turn the handlebar left and right, and the spacebar for the brakes.

The 3D scene is displayed in a perspective projection and the point of view can be adapted manually through mouse and keyboard actions that set the general rotation and translation of the scene. During the vehicle movement, the point of view is defined relative to the motorcycle, meaning that the windows follows the movement of the motorcycle within the scene.

Some visual cues are added to indicate the perceptual information used by the autonomous pilot. For example, some markers displayed as small colored spheres indicate the frontal distance in the direction of movement, as well as the lateral distances to the border of the road at a given distance in ahead of the vehicle. The road can optionally display the outline of the triangulation for a better indication of the movement of the vehicle.

The keyboard/mouse interface also includes some information type of commands, like an update on the point of view and position of the motorcycle within the scene, as well as on the status of the motorcycle in terms of speed, acceleration, etc.

Figure 5 shows the main window of the application displaying the motorcycle and the road with some of the perceptual cues and the outline of the road triangulation.

Pilot Configuration

The second part of our application consists in a GUI written in Python that allows the user to configure the thresholds and constants that define the behavior of the autonomous driver. The interface opens a special dialog for each of the control units of the vehicle.

Figure 6 shows an example of the main pilot configuration window and the configuration dialog for each of the agents composing the pilot. In particular, this figure also displays the values of all the configuration coefficients that we have

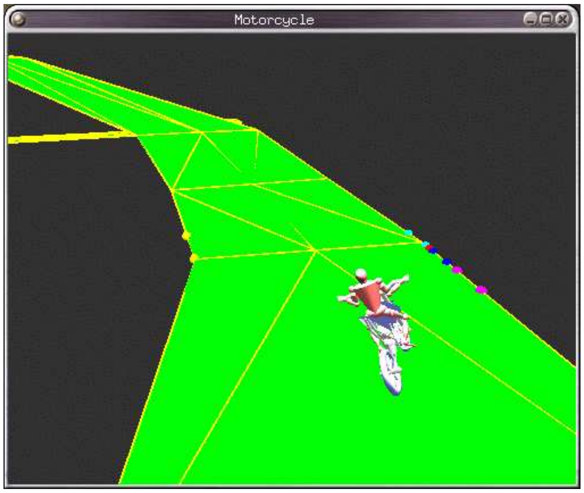
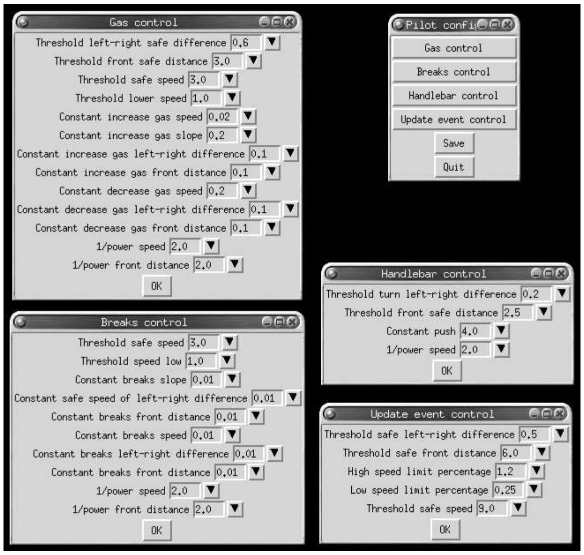


Figure 5: The main application window displaying the vehicle

used for the high reactivity test case mentioned in Section .



Gas control	
Threshold left-right safe difference	0.6
Threshold front safe distance	3.0
Threshold safe speed	3.0
Threshold lower speed	1.0
Constant increase gas speed	0.02
Constant increase gas slope	0.2
Constant increase gas left-right difference	0.1
Constant increase gas front distance	0.1
Constant decrease gas speed	0.2
Constant decrease gas left-right difference	0.1
Constant decrease gas front distance	0.1
1/power speed	2.0
1/power front distance	2.0

Breaks control	
Threshold safe speed	3.0
Threshold speed low	1.0
Constant breaks slope	0.01
Constant safe speed of left-right difference	0.01
Constant breaks front distance	0.01
Constant breaks speed	0.01
Constant breaks left-right difference	0.01
Constant breaks front distance	0.01
1/power speed	2.0
1/power front distance	2.0

Handlebar control	
Threshold turn left-right difference	0.2
Threshold front safe distance	2.5
Constant push	4.0
1/power speed	2.0

Update event control	
Threshold safe left-right difference	0.5
Threshold safe front distance	6.0
High speed limit percentage	1.2
Low speed limit percentage	0.25
Threshold safe speed	9.0

Figure 6: The pilot configuration GUI

Experiments

We have performed our experiments with a circuit consisting of 3 loops such that a portion of it being elevated with respect to the rest of the road. The circuit was designed with the intention to test the ability of the pilot to drive correctly in situations where the road is turning both to the left and to the right, and also where the slope of the road is ascending and descending. Figure 7 shows a perspective view of the circuit that we have used.

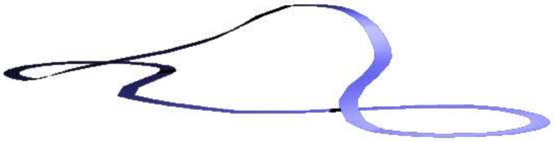


Figure 7: The test circuit

The autonomous pilot was capable of completing the circuit with an average speed comparable to the speed at which a human player is capable of handling the vehicle correctly along the entire length of the circuit.

Beside being successful at completing the circuit, the autonomous pilot has also shown interesting behavior as compared to the human player. In the case of the human, the entire set of control keys is rarely used and once the player achieves a speed that is perceived as comfortable, the rest of the circuit is covered by controlling only the lateral movement of the motorcycle. In the case of the automatic pilot, we can observe a higher variation of the speed, which makes the simulation closer to a real-life situation.

Considering the general direction of movement, we have also observed that the autonomous pilot is much more sensitive to the differences between the left and right distance to the border of the road than the human player and the changes in direction happen a lot more often. The pilot also seems to be capable of remedying dangerous situations better than the human player but the general impression of the ride is that it is less smooth.

To evaluate the autonomous pilot, we have computed a number of statistics based on 5 completed circuits by the autonomous pilot as well as by two human subjects. Table 1 shows these results in which the rows have to following meaning: average time to complete the circuit (time), aver-

Table 1: Comparison of the performance of the autonomous pilot and the human players

	Human 1	Human 2	Pilot	Percentage
Total time	97.4	79.2	357.9	405%
Average speed	6.19	8.94	2.2	29.06%
Maximum speed	8.75	12.26	6.34	60.32%
Total distance	2312.05	2316.83	2465.39	106.52%
Left turns	121.4	119.2	277.4	230.59%
Right turns	51.4	47	185.3	376.63%
Lateral balance	0.29	0.36	0.66	205.36%
Exit the road	0	0.4	3.9	1950%
Frames to recover	0	11.2	9.36	167.21%
Completed circuits	0	0	45.45%	
Perfect circuits	100%	60%	20%	25%

age speed over the entire circuit (v), maximal speed that the player has achieved at any time(max v), the average value of lat_{abs}, the total distance covered to complete the circuit, the total number of left and right turns, the number of times that the player has exited the road. The last row shows the number of times that the pilot has exited the road with no immediate recovery, in which case the experiment was restarted.

From this table we can note that the average timing of the human player and of the autonomous pilot are comparable, even though the human can still handle higher speeds. Experiences with higher speeds for the pilot resulted in the vehicle leaving the road without managing to recover.

Conclusions

In this paper we have presented an application simulating a motorcycle that can be driven by both a human player and an autonomous pilot. The application is implemented based on the physical equations describing the vehicle's attributes, motion, and road behavior. The physical model of the vehicle has been described in Section .

The main focus of the paper has been the description of the automatic pilot. This part of the application is implemented using a multi-agent model in which each control unit of the vehicle, like the throttle, the handlebar, and the brakes, is controlled by an independent agent with a probabilistic behavior. Section described in details the equations used by each of the agents to drive the vehicle.

The experiments described in Section have shown that the autonomous pilot is capable of successfully driving the motorcycle over the entire length of a test circuit in conditions that are comparable to the performance of a human driver.

As a limitation of our system in its current state, the coefficients that determine the behavior of the pilot have to be chosen by the user and the task of finding good values for them is a tedious one. As a direction for future research we intend to explore some methods that would allow the agents to find the appropriate behavior through adaptation and learning.

References

Abdelzaher, T. F.; Atkins, E. M.; and Shin, K. G. 2000. QoS negotiation in real-time systems and its application to automated flight control. *IEEE Transactions on Computers* 49(11):1170–1183. Best of RTAS '97 Special Issue.

Anderson, J. D. J. 2001. *Fundamentals of Aerodynamics*. McGraw-Hill.

Atkins, E. M.; Miller, R. H.; VanPelt, T.; Shaw, K. D.; Ribbens, W. B.; Washabaugh, P. D.; and Bernstein, D. S. 1998. Solus: An autonomous aircraft for flight control and trajectory planning research. In *Proceedings of the American Control Conference (ACC)*, volume 2, 689–693.

Bourg, D. 2002. *Ohysics for Game Developers*. O'Reilly.

Gavrilets, V.; Frazzoli, E.; Mettler, B.; Piedmonte, M.; and Feron, E. 2001. Aggressive maneuvering of small helicopters: a human centered approach. *International Journal on Robotics Research*.

Kelly, T. 1997. Driver strategy and traffic system performance. *Physica A* 235:407–417.

Martinos, I.; Schouwenaars, T.; De Mot, J.; and Feron, E. 2003. Hierarchical cooperative multi-agent navigation using mathematical programming. In *Proceedings of the Allerton Conference on Communication, Control and Computing*.

Al-Shihabi, T., and Mourant, R. 2003. Toward more realistic behavior models for autonomous vehicles in driving simulators. *Transportation Research Record* (1843):41–49.

Mot, J. D., and Feron, E. 2003. Spatial distribution of two-agent clusters for efficient navigation. In *IEEE Conference on Decision and Control*.

Mourant, R., and Marangos, S. 2003. A virtual environments editor for driving scenes. In *Proceedings of the International Conference on Computer, Communication and Control Technologies*, volume IV, 379–384.

Mourant, R., and Refsland, D. 2003. Developing a 3d sound environment for a driving simulator. In *Proceedings of the Ninth International Conference on Virtual Systems and Multimedia*, 711–719.

Nagel, K. 1996. Particle hopping models and traffic flow theory. *Physical Review E* 53:4655.

Sukthankar, R.; Baluja, S.; and Hancock, J. 1998. Multiple adaptive agents for tactical driving. *Applied Intelligence* 9(1):7–23.

Weiss, G., ed. 2000. *Multiagent Systems: A Modern Approach to Distributed Artificial Intelligence*. MIT Press.

Wooldridge, M. 2002. *Introduction to MultiAgent Systems*. John Wiley & Sons.