Visual control of driving and flying: Importance of optic flow rules, perceptual representation of 3-D space, and internal models of vehicle dynamics

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Abstract – *Basic research on the visual control of locomotion has focused on optic flow rules that connect specific features of the optic flow field (e.g., global radial outflow, tau, and splay rate) with specific actions (aiming, braking, and alignment with a path, respectively). There is growing recognition that, while optic flow rules are important, visual control of vehicles involves much more, including perceptual representation of 3-D space and internal models of vehicle dynamics. Here I briefly describe experiments on a variety of visually-controlled maneuvers performed with ground vehicles and aircraft, both real and simulated, showing the importance of optic flow, 3-D space perception, and internal models of vehicle dynamics.*

Introduction

Over the past half century, there have been many studies dealing with visually controlled locomotion. Some of this work has been fundamental research with the goal of understanding the visual control of locomotion, and some of the work has addressed applied issues relating to driving safety, flight safety, robotics, the development of autonomous vehicles, and the development of flight displays. Over this time, there have been two quite distinct conceptions of how vision is used to control locomotion. One approach, taken mainly by control theory specialists, has been to conceptualize the control of a vehicle relative to 3-D distal variables in the environment (position relative to roadway markers or altitude above the ground and their temporal derivatives) and to come up with formal control models that characterize the control inputs of the human pilot/driver (e.g., Dickmanns, 1992; Donges, 1978; McRuer *et al*., 1977). The second approach, inspired by James Gibson during the 1950's (e.g., Gibson, 1958; Gibson *et al*.,

1955) and pursued mostly by perceptual psychologists, has focused on perspective information, especially 2-D optic flow, as the input to visually controlled locomotion. Gibson had the important insight that 2-D optic flow rather than visual information about 3-D layout is often a sufficient input for visually controlled locomotion. For example, the global radial outflow of the translational flow field specifies the instantaneous direction of motion (Gibson *et al*., 1955), the optical variable tau specifies the time for the eye of an unaccelerated observer to arrive at the location of a surface (time-to-contact) (Lee, 1976), and optical splay rate of a straight line on the ground plane provides an efficient basis for turning into alignment with the line (Beall & Loomis, 1997; Calvert, 1954).

Aiming and braking judgments and behavior Much of the recent experimental literature on visually controlled locomotion in the last 25 years has focused on two pairs of tasks, largely inspired by ideas about optic flow developed by Gibson and his followers (e.g., Lee, 1976). Each pair consists of a psychophysical task of perceptual judgment and a corresponding active control task. The first pair involves the judgment of one's travel direction (aimpoint) and the control of aiming with respect to a point in the environment. The theoretical idea motivating this research is that global radial outflow specifies instantaneous direction of travel (aiming), which is two-dimensional in the general case of travel through air or water but often constrained to one dimension.

There are two obvious examples of one-dimensional aiming. The first is the pilot's control of the airplane's descent with respect to the intended touchdown point on the runway (where alignment with the runway has already been established). The second is lateral aiming of a vehicle or an observer's body toward a point on the ground plane; here the observer steers left or right. Active control of aiming has been studied relatively little (e.g., Rushton *et al*., 1998; Warren *et al*., 2001) while much more research has been devoted to psychophysical judgments of aiming under the rubric of "heading perception" (e.g., Crowell & Banks, 1993; Royden *et al*., 1994; Macuga *et al*., 2006; Warren & Hannon, 1990). These studies have employed discrete trial psychophysics in which a brief presentation of optic flow is presented to a passive observer, who then makes a judgment of the simulated travel direction with respect to a target. While aiming is a very specific task, the perception of heading and more generally the perception of 2-D travel direction, may be of broader significance, for they may be involved in the control of other spatial tasks such as steering a curving path and control of altitude during terrain following.

The other pair of tasks involves the perception of "time-to-contact" and the active control of braking; these tasks have been largely motivated by Lee's theoretical analysis of braking in terms of tau (Lee, 1976). A number of have been done on the active control of braking (e.g., Fajen, 2005, 2006, 2007; Yilmaz & Warren, 1995) and provide support for the idea that the optic flow can be used to regulate braking. Associated perception studies have used discrete trial psychophysics, in which subjects make judgments relating to time-to-contact (e.g., Kaiser & Mowafy, 1993; Tresilian, 1991).

Given the wide variety of spatial behaviors that make up visually controlled locomotion, it may seem odd that so many studies of the past two decades have focused on these four tasks. Because aiming judgments deal with direction and braking and time-to-contact judgments deal with the approach to a surface, it is plausible that other forms of controlling locomotion with respect to surfaces might be reducible to a succession of aiming and time-to-contact judgments. An example is the analysis of Loomis and Beall (1998) of how a pilot of an aircraft might judge whether the aircraft is going to pass clear of the ground during a pull-up maneuver following a dive; they suggest that if a succession of aiming judgments indicates that the aim point of the aircraft on the flat ground surface is accelerating toward the horizon, the pilot can correctly conclude that the aircraft will pass clear. (This will be discussed in more detail at the DSC 2010 meeting.) Generally, however, most researchers interested in other forms of visually controlled locomotion, such as steering a curving path or terrain following, have not attempted to analyze these behaviors in terms of aiming and braking judgments. Thus, the substantial amount of research devoted to aiming (including heading) and braking seems to have not taken us very far in understanding visually controlled locomotion more generally.

Analysis of a broader range of maneuvers Adopting this view, Loomis and Beall (1998) argued that there are a number of important visually-based maneuvers that require their own specific analyses in terms of stimulus support and perceptual process. For example, in other work these authors showed that when steering a straight path in the presence of lateral perturbing forces when the path is defined solely by continuous lane markers and no other visual information is present, steering cannot be understood in terms of heading perception because information about heading is unavailable, inasmuch as there is no information about the velocity component parallel to the path (Beall & Loomis, 1996). In this case, they showed that splay rate of the lane markers was the primary stimulus variable used for steering. Other behaviors not likely to be understood solely in terms of the perception of heading and time-to-contact are steering a car along a curving path (Donges, 1978; Godthelp, 1986; Kelly *et al*., Land & Horwood, 1995; Land and Lee, 1994; Salvucci & Gray, 2004), turning into alignment with a straight path (Beall, 1998; Beall & Loomis, 1997), and terrain following by an aircraft (Zacharias *et al*., 1985). These three behaviors will be discussed in some detail at the DSC 2010 meeting.

3-D space perception and stored representations of the environment Although the treatment so far has focused on optic flow, it is a mistake to assume that optical variables are the primary basis for all cases of visually controlled locomotion. As mentioned above, the classical control theory approach assumed that the controlling stimuli were distal entities in 3-D space, such as lateral position in a road, distance to a lane marker, and distance and direction of an obstacle to be avoided. Although much of the modern experimental literature shows the importance of optic array and optic flow variables, especially in connection with aiming and braking, the strong possibility remains that 3-D space perception is involved in many other behaviors, especially in their near term planning. Perhaps the best indication of this comes from research on open-loop behavior. In tasks involving open-loop behavior, the actor views a target from a fixed vantage point, and then attempts to carry out some locomotor response in relation to the target without receiving further perceptual information about its location. The simplest response is blind walking to the target location (e.g., Loomis et. al., 1992). A more complex response is to view a target and, then with eyes closed, walk along an indirect path to the target (e.g., Philbeck *et al*., 1997). On average, subjects walk to nearly the same location when proceeding along the different paths, indicating accurate perception of self motion. While it is true that optic flow is available when vision is continuous, the possibility remains that such 3-D representations are involved in the planning and regulation of spatial maneuvers both when vision is intermittent and when it is continuous (Loomis & Beall, 2004). In studies of car steering, for example, Godthelp (1985, 1986) and Hildreth *et al*. (2000) found little impact of short occlusions (up to 1.5 sec) on driving performance. More recently, a study by Macuga *et al*. (submitted) showed that drivers were to follow several segments of a simulated road during visual occlusion following a brief visual preview, indicating that they were using an internal representation of the path ahead to continue execution in the absence of vision. In this case, optic flow, when it is available, might then be seen as "fine tuning" the regulation of a maneuver.

Internal representation of plant dynamics Even optic flow rules and 3-D perceptual representations together are insufficient to explain the control of locomotion, for at least one important cognitive representation is also implicated--that of the plant dynamics (Loomis & Beall, 1998, 2004). When we move under our own power or within a vehicle, our locomotion is constrained by the plant dynamics of our body or vehicle; these determine how inputs (to the musculature or to the vehicle controls) result in the subsequent motions of the body or vehicle. A model of the plant dynamics of a vehicle, for example, can be used to predict the linear and rotary accelerations, thence the linear and rotary velocities, and thence the position and orientation of the vehicle in the absence of external perturbations; such perturbations cause position and orientation to diverge from the model predictions. The flight director/autopilot of a modern airliner contains a model of the aircraft dynamics and uses this to predict the near-term consequences of control inputs (in the absence of perturbations). Similarly, a skilled operator who is familiar with the vehicle he/she is controlling has internalized the dynamics of the vehicle well enough to be able to predict its short-term behavior. In driving, this means being able to gauge a comfortable stopping distance, how well the car can take a curve, and the distance needed to pass a car on a two-lane road as well as being to continue to steer the car during temporary visual occlusion. In the piloting of fixed-wing aircraft, this means being able to gauge how sharply a plane can be turned into alignment with the runway, whether the plane will be able to clear a mountain ridge up ahead, etc. One sign of a unskilled operator of a complex vehicle is overcontrolling--using inappropriately large control inputs with moderate to high intermittency. At the other extreme, a highly skilled operator can accomplish the desired maneuvering with a minimum of control inputs. Especially in airplanes, for example, where change of heading is the second integral of control yoke input, a small yoke input can result in very large heading changes over time. Thus, a highly skilled pilot can align an airplane with the runway with minimal yoke inputs provided that they are made at just the right time. It is to be expected that those pilots who have minimal root-mean-squared values of their control inputs during some specific maneuver, such as the landing approach, are those with the best internal model of the aircraft dynamics.

In connection with driving, model-based feedforward control has been the focus of some recent research. Fajen (2007, 2008) found evidence that drivers take into account the maximum braking capability of the simulated vehicle in how they allocate inputs to the braking system over the course of a deceleration and that they learn to adjust their braking inputs in response to changes in the braking system dynamics. As for steering, a number of recent studies have addressed the question of whether people develop internal models of the steering dynamics of a car. As mentioned above, the study by Macuga *et al*. (submitted) demonstrates that drivers can continue to steer a vehicle over several path segments without sensory feedback following a brief period of preview; however, steering performance rapidly accumulated error, indicating that the internal model of steering dynamics was quite noisy. Wallis *et al*. (2002) observed a dramatic failure of open-loop steering -- after observing a simulated two lane road ahead, drivers had their vision occluded and then attempted to sidestep the vehicle into the adjacent lane. Drivers steered the simulated vehicle (without a motion base) toward the adjacent lane but showed no evidence of the opposite turn needed to realign with the lane. This dramatic failure to realign is evidence that drivers have a poor internal model of steering dynamics. Macuga *et al*. (2007) challenged this conclusion somewhat by showing that drivers could do imprecise open loop steering of a three-segment path approximating a lane change or could perform a lane change maneuver when provided with inertial input while driving an electric scooter. Still more recent work by Cloete and Wallis (2009), however, showed that drivers, when attempting to perform a obstacle avoidance maneuver requiring a triphasic steering response, instead produced a biphasic steering response which failed to realign the vehicle with the path. Taken together, the results of the reported research indicates that drivers do not have good internal models of the steering dynamics of a car.

Keywords: driving, flying, visual control of locomotion, aiming, braking, steering, heading, optic flow, tau, splay rate, visual space perception, internal models, plant dynamics, vehicle dynamics

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