# Leveraging Human Movement in the Ultimate Display

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## Abstract

Human movement is a "natural skill" employed to solve difficult problems in dynamics concerning the manipulation of a complex biomechanical system, the body, in an ever-changing environment. Continuous Interactive Simulation (CIS) is a technique that attempts to use this human capacity to solve problems in movement dynamics to solve problems concerning arbitrary dynamical systems. In this paper we test a simple CIS environment that allows a user to interact with an arbitrary dynamical system through continuous movement actions. Using this environment we construct an abstract representation of the well-known pole-cart, or inverted pendulum system. Next we undertake a usability trial and observe the way users explore key features of the system's dynamics. All users are able to discover the stable equilibria and the majority of users also discover the unstable equilibria of the system. The results confirm that even simple movement-based interfaces can be effective in engaging the human sensory-motor system in the exploration of nontrivial dynamical systems.

*Keywords*: Movement, Human Computation, Natural User Interfaces, Dynamical systems

## 1 Introduction

*"We live in a physical world whose properties we have come to know well through long familiarity. We sense an involvement with this physical world which gives us the ability to predict its properties well. For example, we can predict where objects will fall, how well known shapes look from other angles, and how much force is required to push objects against friction. We lack corresponding familiarity with the forces on charged particles, forces in non-uniform fields, the effects of nonprojective geometric transformations, and high-inertia, low friction motion. A display connected to a digital computer gives us a chance to gain familiarity with concepts not realizable in the physical world. It is a looking glass into a mathematical wonderland."* (Sutherland 1965).

These words were originally written by Ivan Sutherland during the 1960s to describe the "ultimate display", a vision of Virtual Reality which is still yet to be fully realised. Aligned with Sutherland's vision we have been using Virtual Environments to try and leverage the human skills related to movement for the particular purpose of solving more abstract problems in mathematics.

In previous work we have described this approach as "Continuous Interactive Simulation" (CIS) since it is based on continuous feedback loops between the user and a simulation of a dynamical system (see Figure 1) (McAdam 2010, McAdam and Nesbitt 2011). These loops are typical of the sensory-motor loops associated with human movement. While human movement is naturally used to solve complex problems in movement dynamics, we try and leverage our natural ability to learn new movement skills in such a way that a user can explore, understand and control arbitrary systems characterised by non-linear dynamics.

**Figure 1. An example of an environment used for Continuous Interactive Simulation**

The key contribution of this paper is a usability study into the effectiveness of a simple CIS environment in engaging a user in sensory-motor exploration of a non-linear dynamical system. The system chosen for this study is the well-known cart-pole system. A more general form of this system is familiar to anyone who has balanced a pole on the palm of their hand. This system was chosen because it is involves non-trivial dynamics, but is also within the capabilities of most people to control (Foo et al. 2000). As a result, failure of users to effectively engage with the system will likely be due to the way it is presented in the CIS environment rather than the dynamics of the system itself. It should be noted that the CIS environment we are using is designed to allow sensory-motor engagement with arbitrary dynamical systems that may have no physical basis whatsoever. As a result, it uses an abstract representation of system dynamics that robs the pole-cart system of its natural affordances.

In our CIS environment the pole-cart system was represented in a multi-sensory virtual environment where the 3D phase space of the pole-cart problem was mapped to a 3D visual coordinate system. The position of a ball was used to represent the system's current state. Stereoscopic display and 3D sound effects were used to enhance the user's spatial cues for the location of the ball in the phase space. The user can manipulate the system state by adjusting the single control parameter by continuously moving a haptic pen constrained to a single dimension.

We carried out a usability trial where 10 users were observed as they spent 2 hours exploring the dynamics of the system. Users were asked to think aloud during the trial and were also interviewed at the end. We report on the users' experiences and exploration strategies when they first interact with the system and how these strategies change over time. All users are able to uncover significant features in the system, namely the set of stable equilibrium points. The majority of users also discover the unstable equilibrium points that are characteristic of this system. Two of the users develop significant skill in manipulating the system during the time frame of the trial. Although a number of further studies are required, the outcomes reported here confirm that movement-based interfaces can indeed be leveraged for the exploration of non-linear dynamics.

## 2 Human Movement

We all continually reach, grasp, gesture, talk, and walk. From time to time we run, jump, swim, sing, dance, and play musical instruments. We write, type, point and click. We use tools, drive vehicles and control machines. We move. Moving proficiently requires that complex hierarchies of movements be mastered and integrated into sequences that achieve specific goals. A movement with a specified purpose or goal is called a skill (Magill 2007).

The ability to adapt movement to suit the conditions has been referred to as "dexterity" and defined as "finding a motor solution for any situation in any condition" (Bernstein 1996). This adaptability of movement has also been described as "physical intelligence" – the "capacity to use your whole body or parts of your body to solve a problem..." (Gardner 1993). In the face of constantly changing environmental conditions and changing goals it is this problem solving capacity that allows us to reliably perform a skill.

In more technical terms, successful performance of a movement skill requires interactive control of the dynamical system consisting of the human biomechanical system and the environment with which it interacts (Neilson and Neilson 2005). This control is performed by the human sensory-motor loop in which the central nervous system receives incoming sensory information from the sense organs and produces motor commands that cause muscles to contract.

For example, shooting a basket in basketball involves motion of the body, the arms and hands in particular, with the hands imparting a force on the ball such that it achieves a trajectory that passes through the hoop. Doing so requires that the dynamics of the physical situation be taken into account by the mechanisms underlying movement. Things to be considered include the dynamics of the human biomechanical system itself, the interaction between the hand and the ball, the ball's trajectory through the air toward the hoop, and the dynamics of the ball's collision with the backboard. Achieving such a feat requires the solution of difficult problems such as prediction, optimisation and control in the face of delayed and incomplete sensory information, time varying nonlinear input-output relationships, and constant disturbance (Wolpert et al. 2001).

A key feature of human movement is the ability to learn new skills. In effect, each new physical situation in which movement occurs represents a new dynamical system for which these problems need to be solved. The mechanisms for solving these problems are provided by complex structures in the central nervous system such as the cerebellum, basal ganglia and motor cortex. The process of learning a new skill involves adapting these mechanisms to a new dynamic situation such that appropriate motor commands are generated in order to produce the desired movement outcome.

Learning new movement skills is a complex process. During the usability trial we wanted to observe if and how users develop skills for controlling the abstract representation of the pole-cart system. For normal motor skills it is known that learning progresses from an initial trial and error exploration and then becomes more purposeful, consistent, stable, permanent, and adaptable over time (Magill 2007). We hoped to observe a similar pattern of skill acquisition as users learned to move within our abstract simulation.

## 3 Understanding Dynamical Systems

A dynamical system is a system whose behaviour can be described in terms of rules that define how the state of system changes over time. There are numerous forms of dynamical system, such as continuous, discrete, stochastic, and so on. We are interested in continuous dynamical systems in which the rules take the form of differential equations. These systems can be used to represent a broad range of behaviours from fields as diverse as physics, engineering, biology, economics, and sociology.

Because the rules for a dynamical system typically involve nonlinear relationships they can be difficult to understand and manipulate. There have been many tools developed to help solve problems concerning the control of dynamical systems. One way in which these tools vary is in the particular user expertise they engage in the problem solving process. Some tools require considerable mathematical expertise. Examples include mathematical software such as Matlab and Mathematica for analysing and solving the equations defining the behaviour of a system (MathWorks 2010, Wolfram Research 2010). Other tools take a particular problem solving technique and present it in a user friendly way. For example, Simulink and Vensim provide a building block approach for constructing simulations of dynamical systems (MathWorks 2010, Ventana 2010). While these tools are still essentially mathematical in nature, much of the mathematical complexity of constructing a simulation is hidden from the user. Even with tools such as these the user may still need considerable mathematical sophistication to ensure that results are valid.

Some tools aim at leveraging domain expertise by further hiding mathematical complexity and allowing a user to formulate problems using the concepts and language of the problem domain (Houstis and Rice 2002). One such tool is RAMSES, which is designed for "non-computer scientists" studying environmental systems (ETH 2010).

Closely related to the simulation of dynamical systems is a means of visualizing the behaviour of a system. This is often used as a means of illustrating a result obtained analytically. Visualisation can also be used to help identify features, such as equilbria or other patterns of behaviour that might not be found using analytical techniques (Groller et al. 1996). Visualization techniques have also been extended to include other sensory modalities such as hearing and touch to enhance the presentation of the system's behaviour (Wegenkittl et al. 1997).

Interactive visualization tools enable users to more rapidly perform simulations, review the results, modify the system and re-run the simulation (Zudilova-Seinstra et al. 2009). Interactive workflows support the process of exploring the behaviour of a system. However, this interaction is usually discrete in nature and directed at presentation factors such at changing rendering techniques or the users point of view. By contrast, computational steering (Mulder et al. 1999, Kalawsky 2009, Tennenhouse 2000) allows the user to modify the parameters of a simulation in order to explore the behaviour of a system under different initial conditions or by some form of intervention during the simulation.

In all of these examples, the human expertise being utilised is of a high-level and cognitive in nature. A very different, low level form of human expertise has also used to solve problems concerning the manipulation of constrained physical systems (Brooks et al. 1990, Witkin et al. 1990) and unstable, rigid body systems (Laszlo et al. 2000). In these cases a user's intuitive motor learning and motion planning skills are used to manipulate a real-time simulation of a system. Our own work builds on these particular ideas.

## 4 Exploring Dynamical Systems

One source of problems regarding dynamical systems that can be difficult to solve concerns the manipulation of a system. Many dynamical systems provide opportunities for intervention that can alter the future course of the system. For example, a dynamical system model of an economy interacting with an environment can be manipulated by varying parameters such as tax rates, controls on emissions from industry, etc (e.g., Kohring 2006). One question that can be asked in such a case is how to manipulate the system to achieve a specific outcome, such as maximising production without causing environmental collapse.

Techniques such as optimal control (Kirk 2004) exist to solve this sort of manipulation problem, but again, these techniques rely on certain assumptions that do not apply to all problems of this sort and where they do apply they require a degree of mathematical sophistication that may be beyond a non-specialist in optimal control theory.

A more general question concerning the manipulation of a dynamical system is – given a dynamical system and opportunities for intervening in that system, what are various ways in which it might be manipulated? Or, more simply, what can be done with the system? For example, what is the effect of various tax and emission control policies on a combined economic/environmental system? In contrast to the problem of manipulating a system to achieve a particular outcome this is a more open-ended question inviting a more exploratory approach. Successful exploration might result in a repertoire of manipulations that illustrate the dynamic possibilities of the system given the available controls.

In our usability study we want to investigate the effectiveness of Continuous Interactive Simulation (CIS) in allowing users to both explore and identify various features of a dynamical system. Our approach makes use of the natural human ability to understand and manipulate the complex physical dynamical systems encountered in human movement. To achieve this we create an environment in which the dynamical system is presented as a "physical" object with which users can interact in purely sensory-motor terms. The behaviour of such an object will initially be unfamiliar to users, but it is intended that through a process of sensory-motor exploration users will be able to learn how the system behaves and how it can be controlled. This process is, of course, familiar to anyone who has attempted to learn a new physical activity. Such an approach requires no domain-specific or mathematical expertise, only the natural expertise we all have in exploring and mastering dynamics of the physical world in which we live.

## 5 A Continuous Interactive Simulation

The CIS environment used in the usability study is capable of representing any continuous dynamical system consisting of up to three state variables and three control variables. This simple environment uses a desktop virtual environment to represent the state of a system using an animated phase space in which the location of a ball in 3D space represents the current state of the system. As the state of the system evolves the ball moves through space. The control variables of the system are manipulated by the user using a continuous input device. The system is simulated in real time so that ball moves according to the dynamics of the system under the influence of the user's movements of the pen.

The desktop virtual environment is shown in Figure 1. It consists of a 3.00GHz dual core Dell T3400 computer, a 120Hz 22-inch monitor, and a Phantom Omni 6 degree-of-freedom haptic pen for input. The 3D visualization was implemented using Microsoft DirectX on Windows 7 with stereoscopic rendering and 3D sound effects to reinforce the ball's position and motion in space. Stereoscopic rendering was provided by an nVidia GeForce GTX 275 video card with nVidia active shutter glasses. The general arrangement is shown in Figure 1. Sound was provided by a Logitech G51 5.1 surround sound speaker system. The dynamical system is simulated using a 4th order Runge-Kutta solver. The simulation and the virtual environment were updated at a rate of 60Hz.

The dynamical system simulated in this study was the well-known cart-pole system. This system is physically characterized by a cart that moves only in the horizontal direction. Attached to the cart by a pivot is a pole that is free to rotate (See Figure 2). There is friction in the pivot and in the wheels of the cart. The dynamics of this system can be expressed in terms of three state variables, i.e., the angular displacement of the pole, the angular velocity of the pole, and the linear velocity of the cart. There is one control variable, the force applied to the cart to move it either left or right. The system has both stable (pole hanging down) and unstable (pole balanced upright) equilibria. The full details of the equations of motion for this system are described elsewhere (Florian 2007).

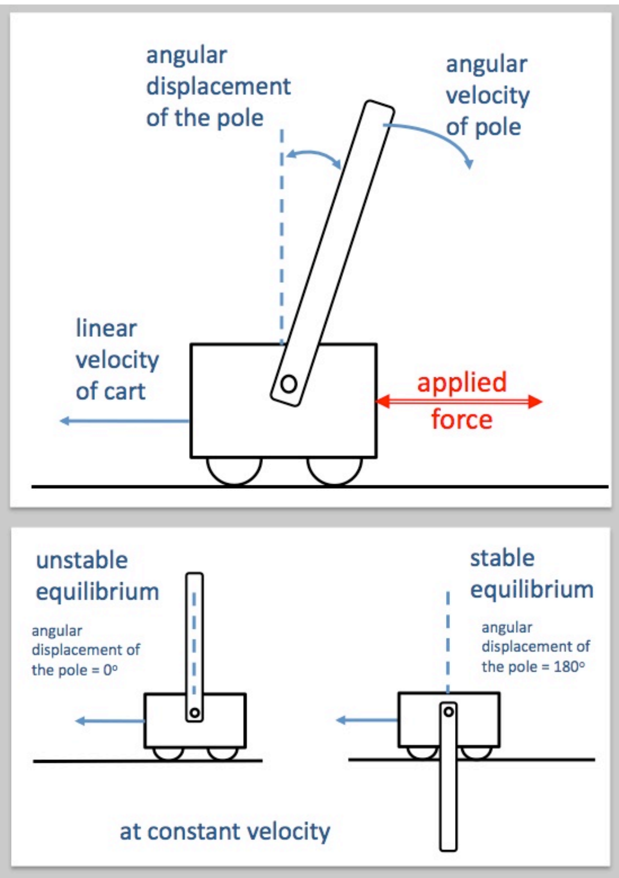


**Figure 2. The physical arrangement of the cart-pole system.**

In our abstract representation of the cart-pole system the 3 state variables, angular displacement of the pole, angular velocity of the pole and the cart velocity are mapped onto the x, y, and z axes of the 3D virtual environment respectively (see Figure 3). This mapping was essentially arbitrary, based simply on the order in which the equations of motion are usually written. The position of the haptic pen (constrained to move only in the +/- x direction) was mapped to the control variable representing the force applied to the cart. A virtual spring returned the pen to the zero position if the user exerted no force on the pen. The user's field of view included six evenly spaced stable equilibria at ($\pm\pi$, 0, 0); ($\pm 3\pi$, 0, 0); and ($\pm 5\pi$, 0, 0); and five equally spaced unstable equilibria at (0, 0, 0); ($\pm 2\pi$, 0, 0); and ($\pm 4\pi$, 0, 0). These equilibria appear to the user as locations in space where the ball can be brought to rest. The equilibria associated with zero velocity of the cart also extend in the ±z direction, applying for other constant velocities.

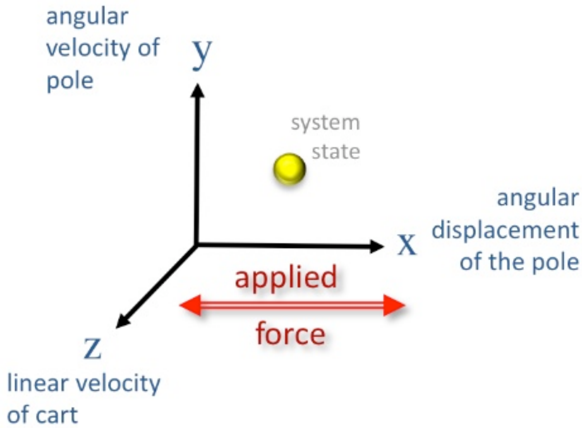


**Figure 3. The abstract representation of the 3D phase space with a ball used to mark the current state. Note that the applied force is constrained by the haptic pen to a single dimension.**

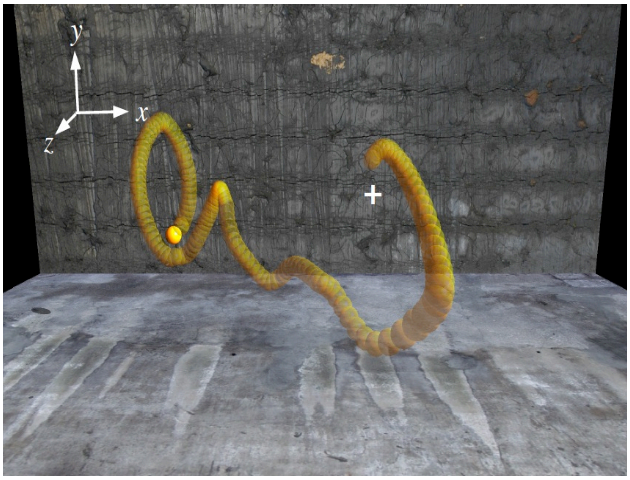


**Figure 4. The user's view of the system's response after a rapid movement of the pen. The trajectory of the ball has been reconstructed for illustration.**

The effect of this abstract representation of the system is to rob it of its physical arrangement from which its behaviour can readily be deduced. Instead, users are confronted with a ball that gives no clues as to how it might behave. Users can only begin to understand how the system behaves through sensory-motor interaction. The user's view of the behaviour of the system in response to a large movement of the pen is shown in Figure 4. None of the users in the usability study recognized the system as having its basis in the dynamics of a physical pendulum. This obfuscation of the physical character of the system served to both prevent users from guessing the behaviour of the system and to illustrate the representation of systems that have no physical basis whatsoever.

We also note that this system was chosen because it exhibits non-trivial, non-linear dynamics and yet is within human sensory-motor capabilities. A more general form of these dynamics are familiar to anyone who has tried to balance a pole on the palm of their hand. If users are not able to deal with this system in our simple CIS environment, then this is likely due to limitations in the way in which the system is presented in the CIS environment rather than the dynamic complexities of the system.

## 6 Usability Study

The study had three aims. The first was to answer the basic feasibility question of whether a simple CIS environment can provide sufficient sensory-motor engagement to allow users to discover important features of a nonlinear dynamical system (stable and unstable equilibria). The second aim was exploratory in nature. We wanted to observe the way users approached their investigation task. Given the unfamiliar non-linear behaviour of the system, what strategies do users take in learning to manipulate the system? Finally we wanted to try and identify usability issues with the interface itself and highlight key areas that would focus further development of our general approach.

A total of 10 adult users, 7 male and 3 female, were recruited from staff and students at a university. All users had normal stereoscopic vision. All were right handed. None of the users had any experience with the analysis of dynamical systems. Each user spent two one-hour sessions exploring the behaviour of the system. At the beginning of the first session users were familiarised with the operation of the virtual environment and given the task of exploring the behaviour of the system looking for stable and unstable equilibria. This was explained to the users as:

- Try and work out how the ball moves and to what extent you can control it with the pen
- Try and find places where the ball comes to rest either of its own accord (stable equilibria) or with you holding it in place (unstable equilibria).
- Mark these places by clicking the button on the pen.

In addition, users were given the following suggestions on what they might do to help them get started:

- Do nothing
- Try small and large movements of the pen
- Try slow and fast movements of the pen
- Try these things at different points in the path of the ball

Users were asked to record the location of equilibria by pressing a button on the haptic pen that left a marker at the current location of ball (see Figure 5). Users were encouraged to "think out loud" as they explored the behaviour of the system. All user sessions were video recorded.

At the conclusion of the final session, users were asked the following general questions:

1. What was your overall impression of the experience?
2. What particular difficulties, if any, did you have in performing the task given to you?
3. The motion of the ball represents the behaviour of a real world physical object. Do you have any idea what that object might be?

## 7 Results

All users were able to discover the equally spaced stable equilibria at (±π, 0, 0); (±3π, 0, 0); and (±5π, 0, 0). Once reached these locations are characterized as places in the phase space were the ball stays at rest. Furthermore all users discovered the set of stable equilibria related to constant cart velocities at (±π, 0, ±z); (±3π, 0, ±z); and (±5π, 0, ±z). These equilibria extended along a line in the ±z direction from each zero velocity stable equilibrium. Figure 5 illustrates one users progress toward identifying the stable equilibria.

Eight of the ten users were also able to identify the existence of equally spaced, unstable equilibria that lie between the stable equilibria at (0; 0; 0); (±2π, 0, 0); and (±4π, 0, 0). Two users also correctly identified that constant cart velocity unstable equilibria also extended from these zero cart velocity equilibria in the ±z direction.

These results show that the abstract representation of the cart-pole system provided by the simple CIS environment described is sufficient to allow the equilibria of this system to be identified by users with no knowledge of the analysis of dynamical systems.

**Figure 5. A user's progress toward identify stable equilibria. The user has marked six equally spaced zero cart velocity stable equilibria in the x-direction. The user has also marked constant cart velocity equilibria extending from the two left most zero velocity equilibria in the ±z-direction. The trajectory of the ball has been partially reconstructed for illustration.**

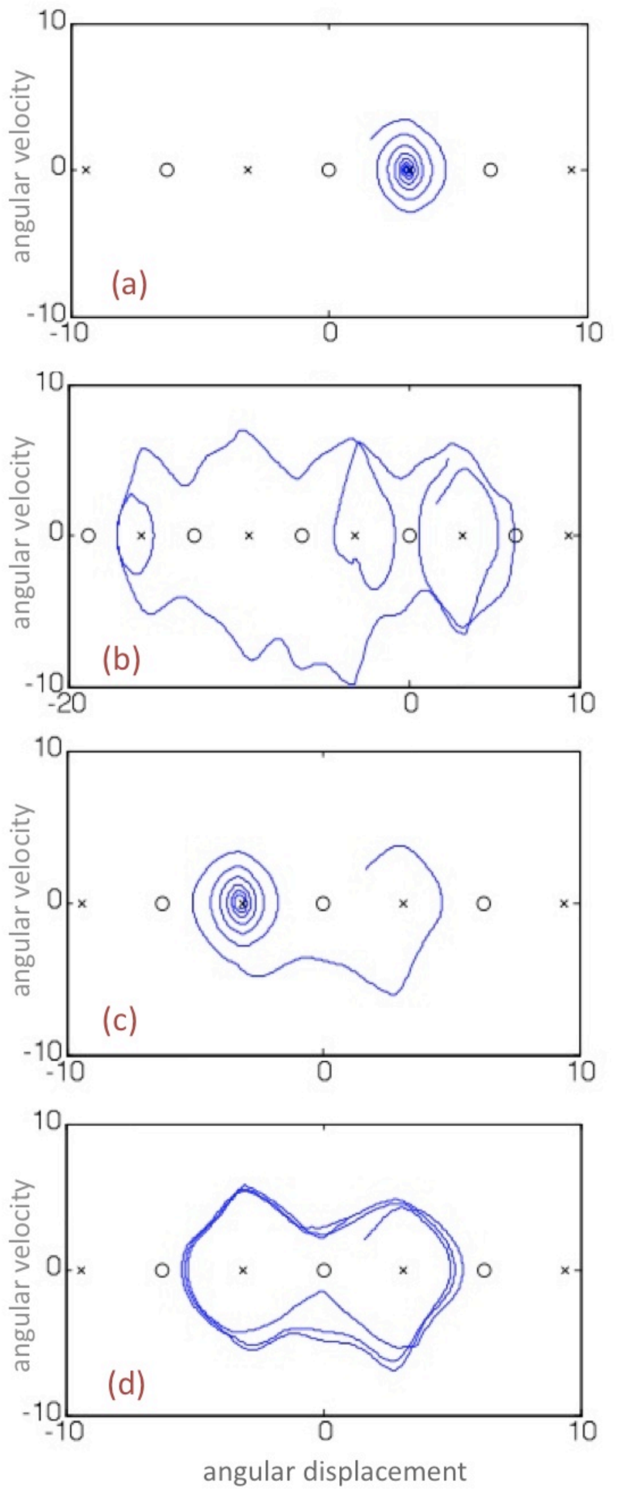


**Figure 6 Plots of angular displacement versus angular velocity illustrating a user's increasing familiarity with the cart-pole system. Crosses indicated stable equilibria. Circles indicate unstable equilibria. (a) Intrinsic dynamics of the system with no user input (b) Initial interaction (c) Deliberately perturbing the system toward another stable equilibrium (d) Orbiting two adjacent stable equilibra in order to "probe" the intervening unstable equilibrium.**

We also examined the recorded trials to try and ascertain how users learned to control the system. Individual experiences and the users level of achievement varied considerably. However, the users' pattern of engagement with the system was consistent. All users appeared to progress through similar phases of discovery corresponding to initial interaction with the system, discovery of stable equilibria, and discovery of unstable equilibria. The following sections summarize the key observations made during each of these phases. To help illustrate these learning phases the response of the system to user input for one user is shown in Figure 6.

## 7.1 Initial interaction

A user's initial attempt at interacting with the system was universally met with surprise. All users commented on two striking features of the system's behaviour. Firstly, the ball moved in three dimensions while the pen only moved in one dimension. Secondly, the ball behaved very erratically in response to movement of the pen, often bouncing rapidly out of view if the user made a rapid movement of the pen.

After this initial surprise, users set about making exploratory movements of the pen to try and work out the relationship between movement of the pen and movement of the ball. In most cases users made continuous and often large movements of the pen rather than letting the intrinsic dynamics of the system play out without their intervention. As a result early interaction was characterised by large erratic excursions of the ball through space, as illustrated in Figure 6b. This resulted in some users expressing a degree of frustration with the difficulty of the task. If this occurred, they were reminded of the initial suggestions they had been given, which included doing nothing.

As it became apparent to users that the relationship between their movement actions and the response of the system was not at all straightforward, users tended to adopt a somewhat more systematic approach. They would begin by allowing the ball to settle into a stable equilibrium after which they would make a short movement of the pen and then observe the subsequent behaviour of the ball. This allowed users to perturb the system and then observe the intrinsic dynamics of the system, which would bring the ball to rest at one or other of the stable equilibria. This approach allowed users to discover a number of the stable equilibria, although the particular equilibria discovered was largely a matter of chance.

## 7.2 Discovering stable equilibria

The essentially random discovery of stable equilibria characteristic of a user's initial interaction with a system was enough to alert users to the overall topological structure of the system's equilibria. With the knowledge that multiple stable equilibria existed several users hypothesised the existence of additional equilibria that they had not yet located realising that the stable equilibria were probably equally spaced.

Verifying that an equilibrium existed at a particular position required that the user manoeuvre the ball into that position. This required users to try and learn how to control the ball in order to put it where they wanted. Without too much trouble users were able to work out the movements required to the move the ball either to the left or the right, from one stable equilibrium to another.

However, when moving between equilibria, users initially had difficulty in controlling whether it was the equilibrium immediately adjacent to the starting equilibrium or one further away. Reliably manoeuvring the ball into an adjacent equilibrium required more precise control over the magnitude and timing of the pen's movement. Eventually all users were able to do this semi-reliably (i.e, they could move the ball into an adjacent equilibrium, but it may take more than one attempt). Three users were able to reliably move the ball from one stable equilibrium to another stable equilibrium of their choosing, as illustrated in Figure 6c.

A further feature of the system discovered by all users was the existence of additional stable equilibria for constant velocities of the cart. Users discovered these by making small slow movements of the pen starting with the ball at a stable equilibrium. The ball would move forward and backward and could be brought to rest at any point on a line extending in the ±z direction from a stable equilibrium with a fixed displacement of the pen (constant force on the cart). These constant velocity equilibria were typically discovered after the equally spaced zero velocity equilibria, although two users discovered them first.

All but one user managed to discover all of the stable equilibria in the first one-hour session. The remaining user completed their discovery of all of the stable equilibria early in the second session.

Another observation made during this phase of discovery was the way in which users described the behaviour of the system. Users had been asked to "think out loud" and so were forced to try and put the behaviour of the system into words. While users appeared to be trying to describe similar structures and behaviours they used very different language to do so. A region of erratic behaviour was described as a "vortex", a "ladder" and even "the zig-zaggy place". The attractive regions surrounding the lines of constant velocity equilibria were variously described as "cylinders", "channels", "lanes", "tunnels", "magnets", and "quantum wells". The motion of the ball was variously describes as "falling", "flying", "bouncing", "skipping", "floating", and "gravitating". Movement of the pen was described as "pushing", "pulling", or "flicking".

The use of language such this seemed to be most prominent in the early stages of exploring the system. As users became more adept at controlling the ball they seemed to spend less time talking about what they saw the system doing and more time just interacting with the system, perhaps stopping occasionally to comment on something new they wanted to demonstrate.

## 7.3 Discovering unstable equilibria

Eight of the ten users were able to correctly identify that an unstable equilibrium existed between each pair of stable equilibria. Discovery of these appeared to be more difficult for users and only occurred in the second one-hour session and after users had discovered the stable equilibria.

Identifying an unstable equilibrium seemed to occur when the ball came within sufficiently close proximity for the ball to slow to almost a complete stop before accelerating away again. Typically this would have to happen on a number of occasions before a user actually noticed the ball slowing to a near stop and deduce that there might be another equilibrium present.

In order to more precisely locate the position of an unstable equilibrium, several users adopted a "probing" strategy in which they would repeatedly launch the ball from a stable equilibrium toward the region containing the unstable equilibrium. One user in particular seemed to become quite skilled at probing the region between two stable equilibria by circulating the ball in an "orbit" around both stable equilibria approaching the unstable equilibria during the ball's passage between the stable equilibria, as illustrated in Figure 6d. This allowed the user to deduce that the location of the unstable equilibrium was at the point directly between the stable equilibria.

The two users who were not able to identify the existence of any unstable equilibria had both been only partially successful at deliberately moving the ball between adjacent stable equilibria. Both users expressed some frustration during the second one-hour session when it became clear that they were not making any new discoveries or becoming any more adept at controlling the ball.

Of the eight who did identify the zero cart velocity unstable equilibria, only two users went on to correctly identify the constant cart velocity equilibria extending in the in the ±z direction from each of these. These users were two of the three users who were able to reliably pass the ball between adjacent stable equilibria, suggesting that this skill may have been a prerequisite for discovering more subtle aspects of the system's behaviour.

An important observation during this phase of discovery was that while eight out of ten users correctly identified the existence of the unstable equilibria, no user developed sufficient skill to be able to maintain the ball at an unstable equilibrium for any length of time.

## 7.4 User impressions

When asked for their overall impression of their experience with the system at the end of the study user feedback varied considerably. Perhaps unsurprisingly, the users who provided the most positive feedback were those who met with most success in learning how the system behaved and how to control it. These users described the experience as "challenging", "fun", and "absorbing". Users who had more difficulty typically had a less sanguine view of the experience describing it as "frustrating", "difficult", "tedious", and "really, really hard".

A sense of progress and achievement seemed to be important to a user's view of the experience with one user saying that it was "quite tedious" until they discovered a new aspect of system's behaviour that made them want to know "what more can I do with this?". This same user described the experience as becoming more fun as they got better to the point where they felt that they "owned the ball" suggesting, in their own mind at least, that they had in some way mastered the problem given to them.

All users cited the unexpected behaviour of the ball in response to movements of the pen as the chief difficulty that they had in exploring the behaviour of the system.

The users who did manage to identify unstable equilibria noted the difficulty in precisely locating the position of an equilibrium and then maintaining the equilibrium. Reasons given for this difficulty included that they had had insufficient practice, that the region of space into which they had to maneuver the ball was too small, and that the ball was moving too fast. Interestingly, none of the users jumped to the conclusion that it might not be possible to maintain the ball in unstable equilibrium (indeed it is not impossible).

At the end of the study all users were asked to speculate on the nature of the system represented by the behaviour of the ball. This proved to be very difficult for users and in fact none of the users were able to hazard any guess as to what the system might have been.

## 8 Discussion

The cart-pole system used in this study is a system possessing non-trivial, non-linear dynamics. When presented in abstract form in a simple CIS environment the system is stripped of any clues as to its behaviour provided by the physical arrangement of its parts. Nonetheless, users were still able to explore the behaviour of the system and correctly identify the existence of stable and unstable equilibria. While the abstract representation made the task of discovering the behaviour of the system much more difficult than it would have been had the users been presented with the system in its literal physical form, it has the distinct advantage of being able to represent any continuous dynamical system with up to three state and control variables.

The progression of users through the phases of discovery described in the previous section suggests that their learning experience was consistent with well-known models of sensory-motor learning (Magill 2007). Initial interaction with the system was characterised by deliberate experimentation with the effect of movements of the pen on the motion of the ball characteristic of a "conscious" stage of learning. Users would make mistakes and not know how to correct them. As the study progressed users talked less about what their hand was doing and more about what the ball was doing. This is characteristic of an "associative" stage of sensory-motor learning (Magill, 2007).

Two users achieved a level of skill that might even be considered "automatic" in the time available. This observation suggests that users were indeed engaging with the system in sensory-motor terms. It also suggests that literature on sensory-motor learning might be important in creating user experiences that facilitate the exploration and mastery of novel dynamics presented in this way. For example, what sort of feedback should be provided to users to help them understand and improve their current level of skill in manipulating a system (e.g., Salmoni et al., 1984).

The abstract representation of the system rendered the system unrecognizable to users. It also had a significant effect on the effective dynamics encountered by the users' sensory-motor system. The mapping of the system into the virtual environment meant that displacements of the ball the y and z directions represented *velocities* of parts of the system rather than displacements. This effectively changed the order of the control relationship between the user and the system when compared with the physical incarnation of the system. For this reason, it is not at all clear whether skills obtained with the abstract form of the system would transfer to the physical system.

An important point to note is that in the process of exploring the system in order to find equilibria, users gain some facility in manipulating the system in order to move it between various equilibrium states. Indeed, this is unavoidable since the only means the users have to explore the behaviour of the system is by manipulating it. An important consequence of this is that users discovered not only the existence of equilibria, but also control strategies for achieving those equilibria.

Of course, all of the manoeuvres performed by users with the ball have an equivalent in the physical realisation of the system. For example, the "orbiting" behaviour shown in Figure 6d corresponds to the pole being swung upright so that it passes through the vertical position and falls over. The pole is then swung up again in the reverse direction back through the vertical position, and so on. As the user gets the ball closer to the unstable equilibrium position, the pole slows more at the vertical position. If the ball comes to rest at the equilibrium position then the pole has also stopped at the vertical position.

In terms of developing Continuous Interactive Simulation as a more general approach for studying arbitrary dynamical systems, this study raises a number of usability issues. Chief amongst these are the unexpected response of the system to user input and the presentation of the system in terms of scaling in space and time.

All users cited the entirely unexpected behaviour of the system as the main difficulty they had in exploring the system. This can be characterised as a lack of compatibility between the response of this system and the response of other systems that users are familiar with (Wickens and Hollands 2000). Users may have expected the pen and ball to behave as a pointing device like a mouse with a straightforward relationship between pen and ball behaviour. Whatever preconceptions they may have had, they were dashed the first time they moved the pen.

This lack of preparedness for the behaviour of the system might also be characterised as a "gulf of execution" in which the system does not provide users with the ready means to achieve what they want, i.e. steer the ball (Norman 1988). In most situations user interface design aims to minimise this gap to make an interface straightforward and obvious to use. By contrast we intend to utilise human sensory-motor learning as a means of discovering the relationship between action and system response. In effect, these types of systems require an essential gulf of execution that must be bridged by the human's ability to acquire novel skills.

Despite this, the task of grappling with unfamiliar dynamics should not be made more difficult than necessary. The order in which state and control variables are mapped onto the axes of the 3D visualisation and the haptic pen may be a factor in making the system response more predictable. In the present study the order in which variables were mapped was essentially arbitrary. Had the linear velocity of the cart been mapped onto the x-axis of the visualisation there would have been a strong correlation between left-right right movement of the pen and left-right movement of the ball. This may have reduced the number of mysteries presented to the user by the system.

In addition to the order in which variables are mapped into the virtual environment there is the key issue of how to scale the presentation of the system both in space and time. Indeed scaling in both space and time was implicated by users as a reason for the difficulty they had in maintaining an unstable equilibrium.

The somewhat arbitrary scaling chosen was that the users view encompassed a region of state variables extending from approximately (-20, -20, -10) to (20, 20, 10). This region was chosen so that it included a number of both stable and unstable equilibria and so that the user could explore the global behaviour of the system.

Because the behaviour of the system is simulated, it is possible to simulate the system at different rates. In this study the system was simulated in real time, that is, one second of real time corresponded to one second of simulated time. It is a straightforward matter to simulate the system at a rate faster or slower than this. This detail is of critical importance when dealing with arbitrary dynamical systems in which "real-time" might be measured in micro-seconds or centuries. In such cases scaling of time will be needed so that the behaviour of the system plays out at a rate suitable for sensory-motor interaction.

## 9 Conclusion

In this paper we set out to test the effectiveness of a simple CIS environment in engaging a user's sensory-motor capabilities in exploring a non-linear dynamical system. To answer this we developed a simple abstract representation of the cart-pole problem in a virtual environment. The interface was designed to leverage human movement for continuous interaction with an abstract representation of a simulated pole-cart system.

Ten users completed a 2 hour usability trial where they were required to explore and identify key features of the system dynamics. All users were able to discover the stable equilibria and the majority of users were also able to discover the unstable equilibria. All users were observed to follow consistent patterns of exploration typical of sensory-motor learning. Three users developed significant expertise in manipulating the system. The results confirm that even simple movement-based interfaces can be effective in engaging the human sensory-motor system in the exploration of non-linear dynamical systems.

Future work in developing CIS environments need to address the key issue of how best to design them. Essential to their purpose is providing users with a gulf of execution. However, this needs to be done in such a way that the problem of deciphering the relationship between their movements and the system's response is no more difficult than it need be. One key to such design is the correct use of spatial and temporal scaling to present the system to the users.

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