A Hybrid Physical-Digital Environment for Mediating Complexity in Water Use Scenarios

Extended Abstract

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1. INTRODUCTION

Many problems that deeply impact our lives involve complex systems with many interdependent factors: environmental, economic, political, social, and cultural. Complex systems are especially relevant to sustainability concerns such as energy use and urban development. Successful decision making in these domains often involves adaptive and distributed management [6], where policies emerge out of interactions between a system and multiple people as opposed to a single person setting policies in advance. Policies must reflect a unified, holistic understanding of the entire system, especially where emergent aspects pertaining to human and social dynamics are concerned.

Many social systems can be represented through agent-based models [3], where micro-level behaviors of individual agents result in emergent macro-level phenomena. In some cases, however, it is difficult to approximate the types of decisions humans will make in certain situations, because apart from survey data, it can be difficult to understand what information the agents have available to them and what processes they use to synthesize this information into a holistic understanding of their environment. In these cases, interactive role-playing games have shown success in both making use of real actors to approximate real life behavior (e.g. [2], [7]) and as a form of social intervention (e.g. [5]).

Our efforts to date have focused on the design of hybrid physical-digital simulation environments in which multiple participants representing various roles interact with each other and immersive audio/visual/tactile media through computational models of complex systems. Following Hutchins' model of distributed cognition [8], these systems distribute decision-making intelligence throughout the space and leverage kinesthetic and social awarenesses to assist participants in developing adaptive management strategies that are transferable to real-world situations.

2. GENERAL METHODOLOGY

The interaction uses a 4 × 4 meter square infrared motion capture space using Motion Analysis Inc.'s EVaRT and custom-built motion analysis software to extract real-time features from human motion, including choreographic and interpersonal metaphoric-gesture features based on the physical actions of several participants. Choreographic features concern how participants group themselves in space, in terms of ensembles, duets, soloists, and related structures. Interpersonal gesture features concern how individuals within a group relate to one another in terms of distance, facing, synchrony, and call-and-response behavior. In addition to extracting choreographic features, we analyze participants' motion for physical "effort intentions" based on the acceleration and jerk characteristics of the movements of selected limbs.

These features — choreographic, interpersonal, and effort intention — can be used as inputs to complex systems such those that can be represented by agent-based models. By analyzing correlations between these features and emergent properties of the models, we aim to discover ways in which certain visualization and sonification strategies pertaining to the system state can affect how a user interacts with a system. For example, certain methods of communicating data may demand a user's attention more, drive a user toward or away from a particular state, or result in specific choreographic behaviors. At a higher level, it may be necessary to focus on the overall form or distribution of choreographic or interpersonal states. For instance, a participant who is continually disengaged from the social aspects of the interaction may tend to exhibit low physical interaction with other participants.

This knowledge can provide a baseline to a system of adaptive composition, where the way in which the state of the complex system is visualized or sonified adapts in real-time to assist the participants in their goals that pertain to exploring certain regions of the state space or achieving certain distributions over states. Goals can be ascertained by using probabilistic machine learning techniques (dynamic Bayesian Networks, etc. [9]) to discover trends in participants' exploration of the space. Similarly, the system can then be adapted by optimizing the visualization and sonification strategy with reference to the learned goal, using related methods in optimal control (reinforcement learning, Markov decision processes [1]). This optimization is based on probabilistic relations between system states and previously learned user states.

3. IMPLEMENTATION: AN EXPERIENTIAL GAME FOR WATER USE SIMULATION

Presently, our application of this work has focused on issues pertaining to water supply, regulation, and usage in the state of Arizona. This work also addresses the interplay between water, food, energy, and urban development. A prototype interaction embedding all of the principles discussed above was developed. This prototype incorporated the following actors: an agricultural water user, an urban water user/developer, a single water supplier allocating from three sources (Salt River Project, Central Arizona Project, groundwater), and a regulatory body influencing all aspects of production and consumption by providing taxation on resource exchanges as well as hard limits on specific types of production and use.

The model makes use of a number of high-level features that describe the physical relationships of individuals in the space with respect to each other and virtual objects. Specifically, each water user has access to a collection of virtual objects that represent a destination for water. For an urban water user, for example, these virtual objects may represent indoor versus outdoor water use. Additionally, the supplier player has access to three virtual objects representing sources of water, such as the Central Arizona Project canals, Salt River Project reservoirs, or groundwater replenishment, the last of which can act as a destination of water as well to protect against periodic fluctuations in water availability from the other two sources.

Each participant has a number of features that represent their physical relationships to other objects and people in the space, including:

- Facing: how much is the player facing another player or object?
- Between: how close is the player to being in between two players or objects?
- Distance: what is the distance between players or objects?
- Hand extent: what is the distance that one player is extending his or her hands toward another player or object?

Each of these features can be augmented by a physical effort measure that is tuned to be relevant to the individual feature. For example, facing effort is primarily focused on rotational movement of the sternum, whereas hand extent effort is focused on physical effort of the hands. When augmented, these features not only describe the relations between individuals and objects in the space, but the extent to which a player is expending physical effort to change these relations. Physical effort is measured through a Kalman-EM dual estimation framework [4, 10] that can simultaneously estimate inherent position, velocity, acceleration, and jerk of motion as well as the amount by which movers in the space are placing focus on one specific type of movement based on highly noisy position data. For example, the dual estimation strategy will be capable of detecting whether a user's intent in movement is primarily focused on providing impulses in velocity or acceleration. These features are gestural input to a game in which players exchange water resources by performing various gestures at virtual objects and each other in order to control a flow of water particles traveling between users.

In the resource exchange model, physical effort is used as a summarization of water cost, which may be economic, political, social, or cultural in nature. For example, if an urban water user is gesturing water into outdoor water use with greater physical effort than he or she expends on indoor water use, the outdoor water use will receive the majority of supply. Additionally, exchange of water between users is governed by physical effort, as water that is obtained by the supplier with greater physical effort will require more physical effort from a consumer to obtain. A regulator user can also apply a virtual tax to water use, requiring more physical effort for exchange, by performing gestures in between two players or a player and an object. The physical effort required to regulate may be interpreted as the various pressures weighing against regulation.

All effort curves are calibrated to actual supply curves by the following, novel procedure regulating effort exchange. First, for one epoch and supply amount, Q, define $M(Q)$ as the "marginal supply curve", or the derivative of $Q \cdot S(Q)$ where $S(Q)$ is the traditional (price-quantity) supply curve. In other words, $M(Q)$ represents the economic, social, and cultural cost of supplying one additional unit of water given that Q units already have been supplied. Given a limit of Q_{max} units/epoch, we synthesize N particles, each representing Q_{max}/N units of water, each with effort price randomly and uniformly distributed according to $(Q_{max}/N) \cdot M(Q_{max}/N)$. Given the supplier's effort, E, over the previous epoch, the system transfers the maximum number of particles for which the total effort price is less than E. On average, the effort price of the total quantity of water supplied exactly matches $S(Q)$. In the absence of regulation, let the consumer's effort allocated to a particular activity be C. The consumer will then receive the maximum number of particles for which the total effort price is less than C (unused particles will disappear). In this way, it can be shown that a classical supply/demand equilibrium is reached in both quantity and physical effort and the characteristics of this equilibrium manifest in terms of the overall amount of physical effort occurring within the space. For instance, under extreme drought conditions, all parties will be working extremely hard to both supply and use a very small amount of water. The emotional tension corresponding to this situation is thus given a palpable, physical form.

Next we consider the actions of the regulator, who operates between the supplier and consumer in terms of how particles are transferred. For each source (SRP, CAP, and groundwater), the regulator can limit or tax supply. Additionally, the regulator can limit or tax use for each destination (indoor/outdoor use). The severity of the regulator's actions are determined by his/her physical effort as well as the overall jerk cost or abruptness of the movement. In terms of regulating supply, limitations or taxes can be easily expressed in terms of supply curve adjustments. Letting $S'(Q)$ be the modified supply curve and $M'(Q)$ the corresponding marginal curve, the regulator's action can be expressed as taking each particle and multiplying its effort price by $M'(Q)/M(Q)$. Regarding regulation of use, the regulator can directly "tax" each particle or limit the total quantity of particles available for use.

This prototype provides a high-level gestural vocabulary as input to a model of a resource exchange. In the future, models may also focus on lower-level choreographic features, such as the call-and-response and synchronous behavior features previously mentioned, in order to provide a general input framework that can be applied to multiple complex systems independent of their application or context. Further work also includes a hybrid evaluation plan combining computational metrics with case studies and related ethnographic methods. Computational metrics will focus on overall distributions of choreographic states and attempts will be made to correlate these distributions with specific features found in the case studies.

4. ACKNOWLEDGMENTS

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