Empowerment as a metric for Optimization in HCI

Dari Trendafilov[1,2], Roderick Murray-Smith[2] and Daniel Polani[1]

[1]University of Hertfordshire
Hatfield, UK

[2]University of Glasgow
Glasgow, Scotland, UK

{d.trendafilov,d.polani}@herts.ac.uk,
roderick.murray-smith@glasgow.ac.uk

Abstract

We propose a novel metric for optimizing human–computer interfaces, based on the information-theoretic capacity of *empowerment*, a task-independent universal utility measure. *Empowerment* measures, for agent–environment systems with stochastic transitions, how much influence, which can be sensed by the agent sensors, an agent has on its environment. It captures the uncertainty in human–machine systems arising from different sources (i.e. noise, delays, errors, etc.) as a single quantity. We suggest the potential *empowerment* has as an objective optimality criterion in user interface design optimization, contributing to the more solid theoretical foundations of HCI.

Author Keywords

Optimization, modelling, utility, uncertainty, control.

ACM Classification Keywords

H5.2 [User Interfaces]: Theory and methods.

Introduction

Modern computing devices are increasingly getting new sensing capabilities from physical and virtual sources, which open the opportunity for users to engage in novel embodied interactions. These sources, however, are often subject to significant uncertainty which affects system's usability and has an impact on the design process. At the same time increasing computing power enables us to deal with uncertainty more appropriately, beyond the current ad-hoc approaches. Uncertainty affects human perception of the environment in the process of receiving information from the world, which is followed by cognitive processing and action. Perception is tangled up with specific possibilities of action, called by Gibson [1] 'affordances'. Such affordances are the possibility for use, interpretation and action offered by the environment to a specific type of embodied agent. The potential ability to quantify affordances could greatly benefit HCI design.

Our view on the fundamentals of interaction is that users' behaviour is about them controlling their perceptions [7]. The more control they have over their perceptions the more empowered they are by the user interface to achieve their goals. Conversely, they are less empowered the less they perceive the effect of their actions. Building on work of Powers [7], Klyubin et al [3] introduced the term *empowerment* in its technical sense as an information-theoretic 'universal utility', representing the channel capacity between an agent's actions and its sensory observations in subsequent time steps. *Empowerment* measures the uncertainty in the agent's perceptions related to its actions and thus reflects uncertainty from the agent's point of view, which makes it a suitable optimality criterion when it comes to overall usability optimization of a particular user interface. Other cost functions might, for example, optimize particular system parameters, which are however not directly observed or unambiguously interpreted by the user.

Uncertainty in the Perception-Action Loop

We view the closed loop between user and computer as a dynamic system (Fig. 1), where designers can alter the feedback mechanisms, and where, to an extent, the user can adapt, in order to create an appropriate closed-loop behaviour. Feedback in the perception–action loop is subject to disturbances, as transmission delays and measurement noise, which create uncertainty about the state of the human–machine system and adversely affect usability. The quality of control depends on feedback that must reflect the uncertainty of system beliefs. Interfaces have to deal with uncertainty, not just filter it out [6]. Appropriate use of uncertain feedback could regularise user behaviour and lead to smoother interaction [4].

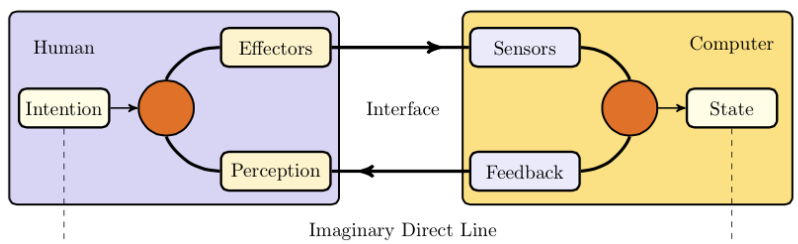

Figure 1: Interaction as closed-loop design.

MacKenzie and Ware [5] have shown lag to degrade human performance in motor-sensory tasks on interactive systems, by an increase in completion time and error rates. Lag is inevitable and can be attributed to properties of input/output devices and software (Fig. 2). Sampling rates of input and update rates of output devices are major contributors. Lag is increased further due to 'software overhead' – a loose expression for a variety of system-related factors. Communication modes, network configurations, number crunching, and application software all contribute.

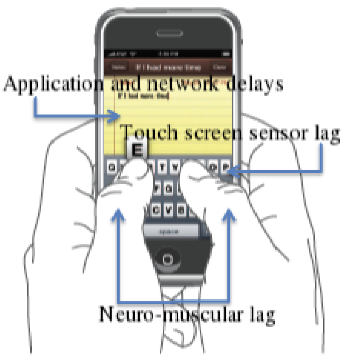

Figure 2: Sources of lags in text entry tasks.

To compensate for varying delays designers need to optimize systems for speed, reliability and overall user experience. There is a trade-off between these factors, since if we would only optimize for speed, the system would behave erratically as delay varies or it would become sluggish if we artificially increased the inherent delay for the sake of stability. Analyzing this trade-off is not a trivial task and requires detailed sensitivity analysis, for which we need proper tools and measures in place. Standard empirical measures for human performance require extensive studies, which come at a price and still pose certain risks regardless of the point density used for evaluation.

In order to break away from the 'discrete-event' paradigm in interaction design, we need to draw on sound principles and formal models, provided by theoretical frameworks handling sensing, modelling and inference, as vital aspects of modern HCI. However, as argued in [8], this has often been lacking in HCI research.

Empowerment as a Measure of Control

Empowerment is defined for stochastic dynamic systems, where transitions arise as the result of making a decision, such as an agent interacting with an environment. It is a task-independent measure and is fully specified by the dynamics in the perception–action loop of the agent–environment coupling unrolled over time. It captures the amount of information that can be injected by an agent into its environment and then perceived by its sensors, and is defined as the channel capacity from the sequence of actions $A_t, A_{t+1}, ..., A_{t+n-1}$ to the perceptions S_{t+n} through the environment $R_{t+1}, R_{t+2}, ..., R_{t+n}$ after an arbitrary number of time steps (Fig. 3), where $\vec{a} = (a_t, ..., a_{t+n-1})$.

$$C(A_t, ..., A_{t+n-1} \to S_{t+n}) = \sup_{p(\vec{a})} I(A_t, ..., A_{t+n-1}; S_{t+n})$$

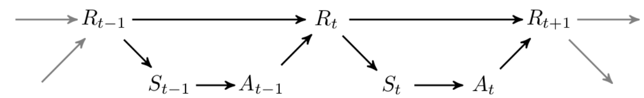

Figure 3: Bayesian network of the perception–action loop.

Intuitively, *empowerment* measures the number of actions available to the user on a logarithmic scale, the outcome of which can be perceived. It is zero if, regardless of the action, the outcome will be the same and is maximal if every action has a distinct outcome. Further examples can be found in [9, 2].

To model the uncertainty and optimize user interfaces we propose the approach of *empowerment* as an objective measure representing how much control the user has in the course of interaction. This approach would allow to theoretically evaluate system's usability in various environmental conditions, as it only requires the probability density associated with the feedback in the perception–action loop.

Optimizing Empowerment in HCI

Empowerment was originally introduced for discrete grid worlds [3] and later extended to continuous domains [2]. A more recent work [9] expands the formalism to the domain of HCI and suggests its potential in making predictions and giving theoretical bounds on standard performance metrics, based solely on properties of the environment. *Empowerment* is conceptually a new quantity, which integrates different types of noise in a single theoretical measure reflecting uncertainty from the agent's point of view. It could provide an analytical tool for performance tuning by revealing critical salient points in the system's design, before resorting to costly empirical studies. Analyzing the trends and the gradients on the *empowerment* curve could give direct insight into the underlying properties and provide confidence regions for the system's parameters. Unlike observational, correlative measures, *empowerment* captures the causal effect, which is a function of the agent's embodiment, describing how the agent's sensors and actuators interact with the environment. Other approaches might optimise elements of the interface which affect the cost function, but which cannot be perceived by the user, whereas by separating sensors and actuators, *empowerment* measures what the agent can actually do as opposed to its environment and perceive as consequences. This makes it a potential candidate for an objective optimality criterion in solving design optimization problems. Models of *empowerment* could predict user performance and users' perception of their own performance and could provide regions for system's parameters trade-off during the design optimization phase. These insights will help designers to make a better choice for systems to evaluate. Using the *empowerment* measure as a first step in the system's analysis will improve quality of design, and at the same time reduce risk and evaluation costs.

However, this approach requires prior theoretical modelling, which, for a particular system, may become too costly. There is a trade-off between the accuracy of the theoretical models and the reliability of the *empowerment* measure – the more accurate the models, the more costly they are to create, but the more reliable the measure they imply.

The aim of this paper is to raise the awareness of the HCI community about the potential *empowerment* has in providing better theoretical foundations for the science of HCI and help inform our understanding of how optimization can further the design of new user interfaces.

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References

[1] Gibson, J. *The Ecological Approach to Visual Perception*. Houghton Mifflin, Boston, 1975.

[2] Jung, T., Polani, D., and Stone, P. Empowerment for continuous agent-environment systems. *Adaptive Behavior 19*, 1 (2011), 16–39.

[3] Klyubin, A., Polani, D., and Nehaniv, C. *Empowerment*: A universal agent-centric measure of control. In *Proc. IEEE congress on Evolutionary Computation* (2005), 128–135.

[4] Körding, K. P., and Wolpert, D. M. Bayesian integration in sensorimotor learning. *Nature 427* (2004), 244–247.

[5] MacKenzie, I. S., and Ware, C. Lag as a determinant of human performance in interactive systems. In *INTERCHI* (1993), 488–493.

[6] Murray-Smith, R. Empowering people rather than connecting them. *International Journal of Mobile HCI 1*, 3 (2009).

[7] Powers, W. T. *Behavior: The control of Perception*. Aldine de Gruyter, 1973.

[8] Thimbleby, H. *Press On Principles of Interaction Programming*. MIT Press, 2007.

[9] Trendafilov, D., and Murray-Smith, R. Information-theoretic characterization of uncertainty in manual control. In *Proc. IEEE conference on Systems, Man and Cybernetics* (2013).