AfterMath: Visualizing Consequences of Actions through Augmented Reality

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Abstract
Computing technology has advanced to a point where computers demonstrate better performance and precision in some analytical tasks than humans. As a result, we see a promising potential to significantly empower our decision-making process by providing relevant information just in time/space. In this paper, we present *AfterMath,* a user interface concept of predicting and visualizing consequences of a user's potential actions. We explore new possibilities through a prototypical system that harnesses physics simulation as a consequence-prediction method and uses augmented reality technology to visualize potential consequences. Finally, we suggest general guidelines for designing systems utilizing this concept.

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Introduction
Half a century ago, Doug Engelbart [9] presented a conceptual framework for augmenting human intellect. Of his ideas, Intelligence Amplification (IA) has grown to be one of the main utilization of today's computers. Advances in computing power, simulation, sensors, data analysis and machine learning make it highly plausible that computers will assist our decision-making process by providing a reliable estimate of the future - given situational and behavioral contexts of user interactions.

A decision-making process includes steps to 1) identify the problem or opportunity, 2) discover possible actions, 3) predict their consequences, and 4) make decisions based on these predictions. The Human-Computer Interaction (HCI) community has been exploring real-time information interfaces that

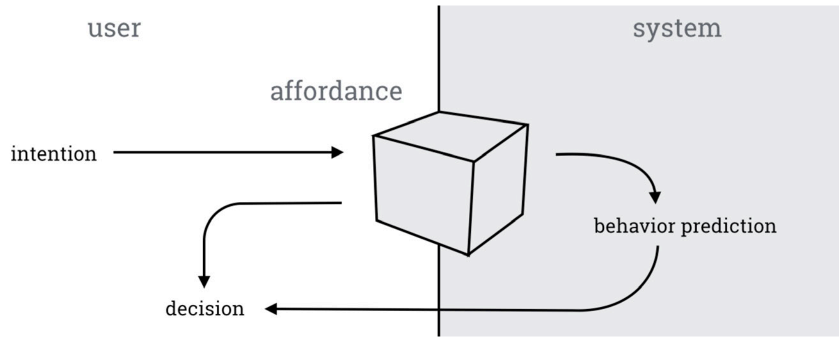

Figure 1. Future behaviors of a system can be estimated and presented to users to assist their decision-making process

assist in decision-making [7, 10, 14, 21, 22, 24], however, these systems were mostly focused on guiding or presenting existing data rather than providing predictions.

User interface design can harness data collection and predictive analysis to provide "insights" about an interaction system. Studies on affordances [13] hint at a good starting point for approaching this concept. Affordances and feedforwards [8, 26] are signals that communicate the possible actions on an object that users can take. By providing consequences of the actions as an additional signal, it is possible to improve the users' insight into how the system in question can be operated.

In this paper, we present *AfterMath*, a user interface concept of visualizing and predicting the possible consequences of afforded actions. Through a physics simulation example prototype, we experiment and show how this concept can be implemented within an actual user scenario. We also provide different patterns and strategies for visualizing and predicting the afforded consequences. Finally, we list some other domains where this concept may be useful.

Related Work

A number of works have presented context-aware computer guided tools that assist users by presenting information about the users' tasks and environment in real-time. Augmented Reality (AR) is a good tool for visual guidance [11], which led to development of AR guided instruction systems including works by Caudell and Mizell [7] and Henderson and Feiner [14]. Allen et al [4] presented an AR system that overlays 3D graphics of already removed materials during an excavation process. ClayVision [24] dynamically alters the scales and motions of buildings in the city to help users to easily navigate. Sixthsense [19] is a wearable gestural interface where a user-mounted projector displays information onto any space/object. These works demonstrated a good exemplary use of AR for real-time information presentation, however, were limited to linking to existing information.

Smart hand tool systems such as FreeD [27], projector guided sculpting [22] and painting [10] systems presented the concept of assisting the user in a creative task by guiding the user based on a pre-defined model of the final desired creation. This concept is very relevant to the one presented here from the aspect of guiding the user to actions with favorable output. However, the key difference is that these systems leverage existing models of desired output as opposed to anticipating the consequences of actions that can potentially be taken by the user.

There also have been many works that address physics simulation in AR [5, 6, 16, 23]. HoloDesk [16], particularly, supports free hand gestures to manipulate virtual objects in 3D. These systems allow interaction only with virtual objects, but potentially, combining with room-sized interaction systems like IllumiRoom [17] or

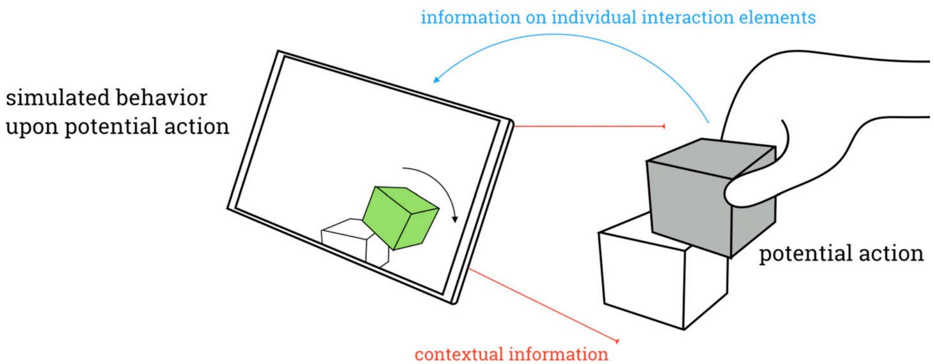

Figure 2. A potential action and its consequences can be analyzed by retrieving information of an individual interaction element and its contextual information. For example, a user's intended (potential) action of putting a block on top of another block can be analyzed to show if the block will stay stable or fall.

RoomAlive [18], they can be powerful tools for predicting kinematics of physical 3D objects in space. Opportunistic Control [15] suggests an interesting variant compared to those systems – leveraging real world affordances for controls in AR systems.

Afforded Action and its Consequences

Affordances describe the set of action potentials that users perceive of an object in situation. They can be differentiated between real (physical) and perceived affordances [20]. Physical affordances provide both visibility and manipulability of an object through tangible input, while perceived affordances (or signifiers) are mainly clues or suggestions for actions that the designer provides to the user.

Graphical perceived affordances can be leveraged as more than just cues for afforded actions. As computer graphics can be controlled dynamically, potential consequences of an action can be visualized upon the user's intention of an action (Figure 2). This interaction concept, which we call Afforded Consequences (AC), has been partially utilized in Graphical User Interfaces (GUIs) for computer applications (e.g. preview windows in Photoshop). However, the use of AC within the physical environment is yet underexplored. Feedforward [8, 26] is also a tool for informing potential results of a given action, however, it differs from AC in two aspects: 1) feedforwards only describe the action itself, not its effects onto the system it belongs to, and 2) AC varies based on the context of the action, therefore, it requires a predictive analysis stage, discussed next (while feedforward does not).

AC Prediction

The key aspect of a system that utilizes AC is its ability to relate an afforded action to its effect onto its surrounding system. Therefore, first, it is crucial that the system is capable of identifying individual interaction elements, their afforded actions, and the context of the actions. Second, the system needs to simulate the ACs of the afforded actions. There are two different ways for predicting ACs: model-driven prediction, and data-driven prediction.

Model-driven Prediction

If we already have a model describing the system's behavior, it can be used for predicting ACs of an action through simulation. For example, if we know all the parameters describing a kinematic configuration, a simple physics simulation can provide likely outcomes of the resulting state induced by a user action.

Data-driven Prediction

If a parameter describing the system is not completely known, or if the system's behavior gradually changes over time, observing its behavior over time could provide a useful database for AC prediction. For example, if a

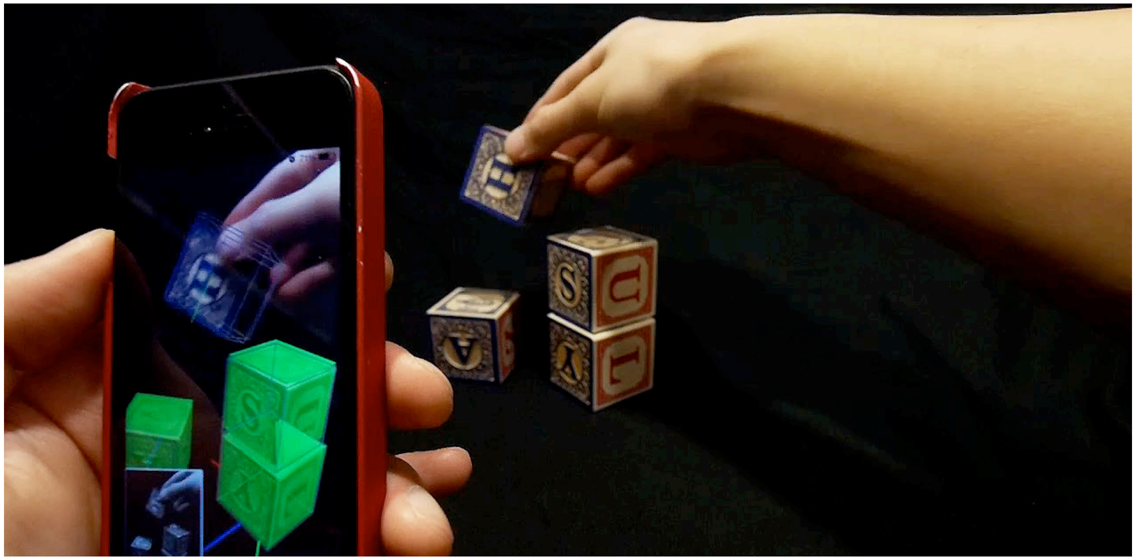

Figure 3. A block-building example. While building a structure with blocks, the AR system automatically constructs a virtual copy of the structure. It is capable of simulating the kinematics of the structure to predict consequences of an action.

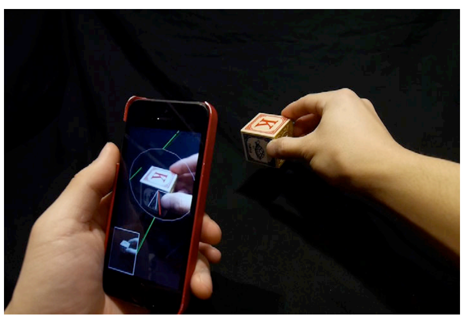

Figure 4. Sensor data from an individual interaction element (a block) is collected and visualized.

block's coefficient of friction is unknown, aggregating motion data over time will help the system to infer the value of that parameter, which can later be used within a physics simulation to get a more reliable AC prediction.

Experimental System

We have built a prototype upon a simple block-building scenario to exemplify the use of the concepts described in the previous sections. We used Vuforia [3] AR library on an iPhone 5s to track individual cubic blocks and recognize the configurations of structures built with the blocks, which is then used in the physics simulations (Figure 3). For an example of data-driven prediction, we used the Arduino Pro Mini and MPU-6050 sensor (accelerometer + gyro) to acquire gravitational force, linear acceleration, and angular acceleration applied to a block (Figure 4). Sensor data is communicated through serial communication between the Arduino, a server computer, and the phone.

Block Building

In this scenario, the phone recognizes the configuration of the user-built block structure and constructs a virtual copy (Figure 3). Using a 3D physics simulation engine (Bullet Physics [1]), the phone understands the underlying kinematics of the structure. The user can navigate through different blocks in the structure to see how removing a block may affect the stability of the structure. The system visualizes these ACs in three different ways: 1) a real-time simulation of the probable result after removing a block (Figure 5 top), 2) marking the blocks (in orange) that will lose stability after removing a block (Figure 5 middle), or 3) color coding the blocks that are safe to remove (green) or not (red) (Figure 5 bottom).

Ramp

The other example is to predict a block's motion on a tilted surface. We used the sensor-augmented block in Figure 4 to recognize its standing position, and determine if the block will slip or not. The coefficient of stationary friction is unknown, so it has to be inferred using data gathered through experiments as shown in Figure 6 top. The gyro sensor is used to detect the moment where slipping begins. Based on the inferred coefficient, the predicted behavior of the block can be simulated and visualized (Figure 6 bottom).

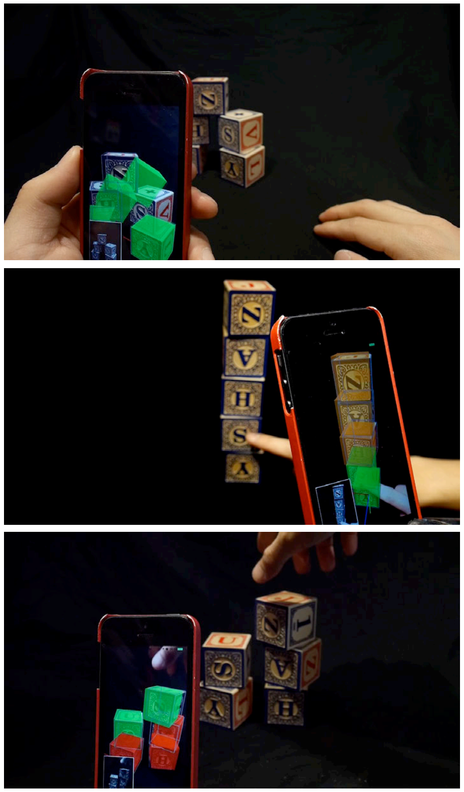

Figure 5. Different ways of visualizing potential outcomes of a block structure after removing a block. Top: real-time simulation, Middle: marking the blocks that will fall after displacing a block (in orange), Bottom: marking the blocks that are safe to remove (green) and not (red).

Potential Applications

AC becomes particularly helpful when the result of an action is irreversible and has some associated cost – usually when it has physical consequences. For example, when a car is approaching a curve, predicted trajectories of the car can be visualized on the windshield. Data about local weather, humidity, and road condition will allow a more reliable estimate.

Based on the prediction, drivers can change speed accordingly to lower the chance of hazard. This scenario is a step forward, after previous driver assistance systems [12, 25] that mainly discussed about navigations and alerts than predictions. Another situation where ACs can be helpful is when people are not capable of a precise prediction - due to lack of information or time to process the information. For instance, a baseball hitter with AR glasses might be able to see a predicted trajectory of a pitched ball – inferred by analyzing the pitching form or based on the pitcher's pitching history. This will allow the hitter to be much better prepared within a short period of time.

Discussion

An important design consideration concerns how an AC can be better visualized. In applications where precise visualization of the AC is important, realistic graphics will be suitable and will require the least mental effort for interpretation. Otherwise, if the implications of the AC are more critical, showing abstract interpretations could be more informative and digestible. Different levels of abstraction strategy can be used [2]. From our block-building prototype we identified and classified three types of AC presentation. 1) *Real-time simulation* (Figure 5 top), 2) *Abstraction of a single AC*: a summary of resulting behavior after a single afforded action (Figure 5 middle), 3) *Abstraction over all ACs*: a summary of ACs after all possible actions (Figure 5 bottom).

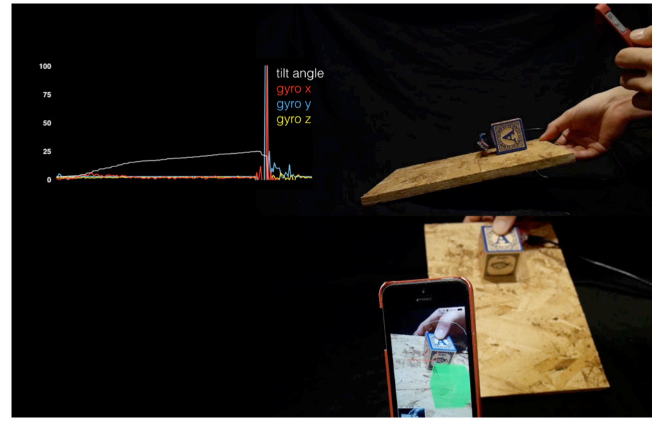

Figure 6. Using data collected through experiments to infer the behavior of a block placed on a ramp (sliding or not).

Conclusion

In this paper, we presented *AfterMath*, a user interface concept for predicting and visualizing the consequences of user actions. Based on given affordances of an object, we predict potential effects of users' actions onto the system the object belongs to. We believe that this will provide "insights" about a system, which might be inaccessible solely via the notions of affordances or feedforwards. Using an example physics simulator and visualizer, we explored different strategies for predicting and visualizing ACs of user interactions.

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