Bits and Bricks

Tangible Interactive Matrix for
Real-time Computation and 3D Projection Mapping

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***Abstract*— The proliferation of projection mapping and computer vision techniques have made it possible to create a multiplicity of dynamic, illuminated environments that adapt to user intervention. This paper describes a unique system for an illuminated, machine-readable matrix of objects that performs real-time computation and dynamic projection-mapping. Illuminated, tangible-interactive matrices have immediate applications as collaborative computation tools for users who want to leverage matrix-based mathematical modeling techniques within a friendly and accessible environment. The system is designed as an open source kit of both off-the-shelf items (such as Lego) and components that are inexpensively fabricated with standard equipment (such as laser cutters). This paper outlines (i) a system of hardware and software for the tangible-interactive matrix, (ii) case study applications of the tangible interactive matrix in various disciplines such as urban planning and logistics, and (iii) discussion of possible directions for future research and experimental design.**

Keywords*— *Interactive Displays; Tangible User Interface; Projection Mapping; Computer Vision; Decision-Support Systems; Collaboration; Lego

I. INTRODUCTION

The tangible interactive matrix in this demonstration is designed to (a) make matrix-based mathematical methods more accessible and intuitive to users who otherwise do not have access to such tools and/or (b) provide an interactive narrative and story-telling device for experts who wish to present or explain matrix-based concepts to non-experts.

A. Mathematical Modeling with Matrices

Matrix-based methods for computation are powerful tools used in many fields and industries (Fig. 1). In particular, they may be used to quickly perform multidimensional calculations over large data sets that are otherwise cumbersome if not impossible to perform by hand. Such methods, however, are largely limited to a subset of experts with some understanding of a computational language (such as python) or proprietary tools.

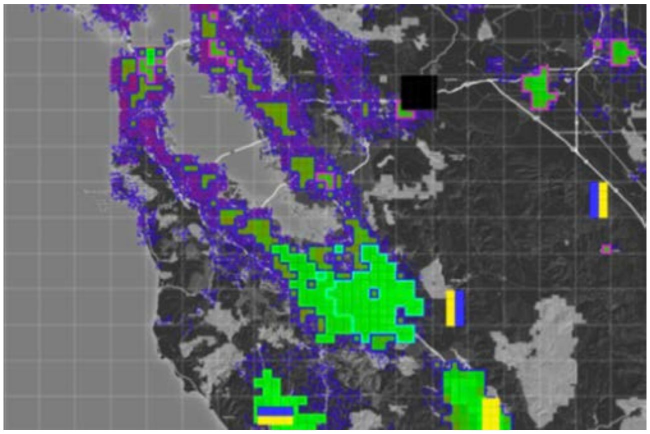

Fig. 1. Matrix-based model for last-mile logistics.

B. Tangible Interactive Computation

Tangible interactive interfaces, particularly when sized for multiple users to be able to gather around a common interface, are ideal for intuitive and collaborative experiences. Tangible interactive matrices have the potential to make existing and powerful mathematical tools more accessible to a broad array of users in many fields and industries.

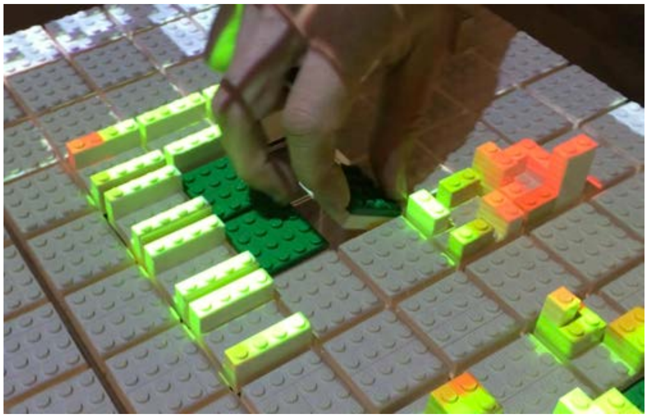

Fig. 2. Tangible interactive matrix model for pedestrian walkability.

Tangible interactive matrices build upon the Urban Data Observatory [5] by offering a concrete technical solution and toolkit for digital interaction in addition to visualization (Fig. 2). This paper also demonstrates applications of tangible interactive matrices beyond urban planning.

This paper presents (a) analysis of the unique features and capabilities of a tangible interactive matrix compared to recent related work, (b) description of the hardware and software involved in a demonstrative implementation of a tangible interactive matrix system, and (c) case studies of the tangible interactive matrix interface applied to three different domains: urban planning, logistics, and crisis resource management.

II. RELATED WORK

Our system extends prior work in tangible tabletop user interfaces for sensing and information display and contributes to the ecosystem of scalable, low-cost tabletop augmented projection tools.

Prior work for augmented reality environments generally perform real-time scanning of the environment using one of two methods: (a) sensing an entire object's 3D shape such as in Sandscape and Phoxel [8][10] or (b) sensing a handful of digitally-tagged objects in the case of Emancipated Pixels, Urp and ReacTIVision [15][16][6]. Method (a), shape scanning, may give the user fine control over the environment, but individual particles (such as sand) cannot be tracked. In the latter method (b), metadata associated with object tags allows objects to become abstractions of hypothetical objects, such a buildings or mirrors, and have the important feature of being tracked as they move. Ullmer and Ishii suggest the concept of physically constrained object tokens [13], however most methods used for scanning such tokens have a distinct capacity limitation that precludes real-time scanning of more than about a dozen tokens or physically constrained spaces. By using NxN arrays of constrained objects, we enable scanning in a way that is cheap in terms of both computation and hardware while facilitating projection-mapping.

Projection-vision systems which detect user interaction and project data in real time are a common way to turn ordinary surfaces and objections into interactive interfaces. For example PlayAnywhere is a self-contained system that sits on a table surface and uses a front-projector with IR computer vision [16]. Other systems may use a projector and sensor system located beneath a transparent table [17][6]. By mounting projector(s) above a table, systems can also project additional information onto 3D tokens [3]. We employ this final variation in our system.

Research shows that tangible interfaces encourage greater discussion in collaborative learning environments [11] and users found patterns in data visualization tasks faster on tangible user interfaces than with only multi-touch screens [1]. The flexibility of such tangible interfaces invites creators from diverse backgrounds to create systems most relevant to them, from interactive tabletop toys for children [7] to data visualization for complex urban planning tasks both in research [2] and government [9] settings.

As such technologies mature, researchers are focusing on producing low-cost and scalable approaches for construction of such systems [12][17] to enable broader audiences to design and create their own tangible interactive tabletop interfaces. In support of accessibility, our system uses readily available and affordable blocks like Lego [4] to simplify construction as well as provide a familiar and playful medium that invites non-experts to engage.

III. SYSTEM

The tangible interactive matrix system (Fig. 3) includes a kit of tagged 3D objects, a table that constrains the placement of 3D objects into a gridded scene, one or more sensors for scanning the scene, one or more computers, one or more display screens, and one or more projectors for projecting light patterns onto the scene. The projected light patterns, via projection mapping, augment the 3D physical scene with information and analytics unique to the user's configuration of the objects.

The system works by first detecting a matrix of uniquely tagged physical objects in real time as they are moved by a user. Next, it performs a real-time digital reconstruction of objects' configuration including form, position, ID, and any metadata and runs a real-time analysis of the objects' configuration. Finally it generates a real-time visualization of the analysis via the display screen(s) and projection maps visual content onto objects on the scene.

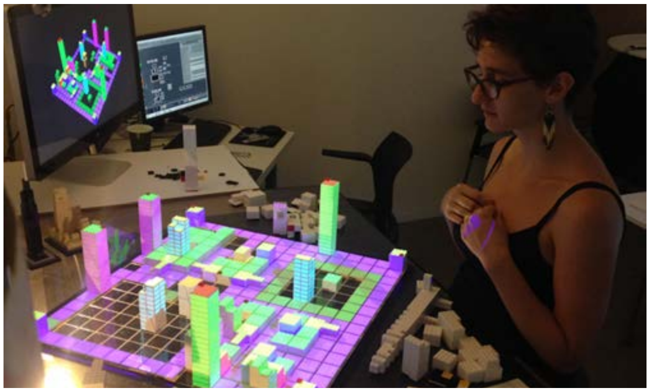

Fig. 3. Demonstrative system with illuminated tangible interactive matrix and 3D projection mapping.

A. *Tangible Objects*

This ability to process (i.e., detect, digitally reconstruct and project light onto) an extremely large number of separate physical objects in real time is facilitated by a novel feature of this device: a user can place the physical objects into a spatial region, but the placement of the physical objects in the spatial region is constrained by a gridded tabletop such that only certain positions are allowed (Fig. 4). A demonstrative system digitally reconstructs and projects light onto 1,936 (44x44) separate physical objects in real time.

Fig. 4. Example Kit of tangible objects viewed from above and below.

B. *Computer Vision*

A user places the physical objects into indentations in the table. The fact that the physical objects on the table are limited to a set of specified positions in a physical grid allows an algorithm to quickly detect and infer the exact location and nature of all pieces (Fig. 5).

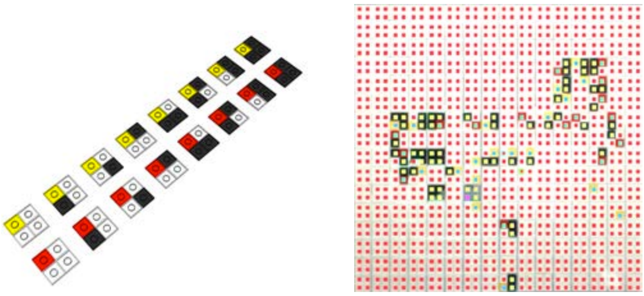

Fig. 5. Machine-readable optical tags for 16 objects with rotation (left) and output of machine-reading applet (right).

C. *Digital Reconstruction and Projection Mapping*

An algorithm merges the location, rotation, and ID data with a digital object repository that uses IDs to link data. The repository contains additional information about object form and any other metadata important to associate with the object. Algorithms perform matrix-based computation and further package a digital 3D model, its meta-data, and any analysis into integrated visualizations for export to display screens or projectors. The user may use the visualizations to influence their next interaction with the system, thus completing a real-time feedback loop.

D. *Tabletop Structure*

For the purpose of scaling and deployment, a tabletop structure has been designed from standard, procurable materials and components such as acrylic and aluminum (Fig. 6 and 7). A grid for constraining placement of objects upon the matrix is cut from acrylic. Dimensions accommodate a 22x22 grid of Lego objects, and the system may concatenate multiple modules.

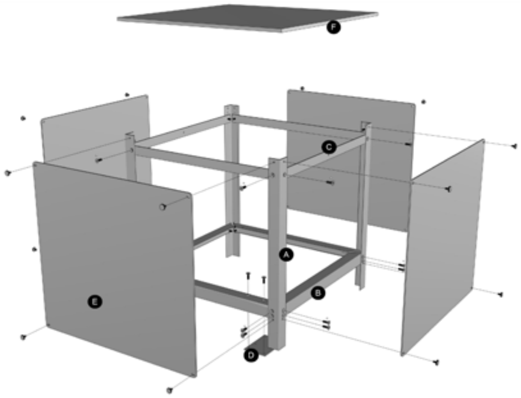

Fig. 6. Diagram of Fabricated Table Components.

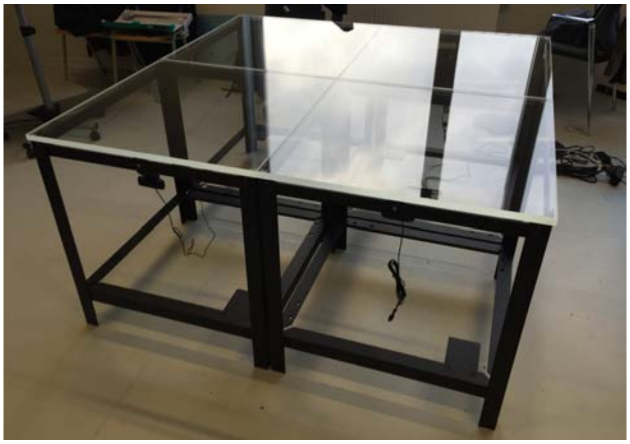

Fig. 7. Four tables concatenated to create a larger system.

IV. CASE STUDIES

The tangible interactive matrix has been applied to various case studies. Each case study leverages some aspect of matrix computation and is unique to a respective field or industry.

A. Urban Planning

A rapid prototyping environment for land use planning and pedestrian walkability was developed jointly with the Development Authority of Riyadh, Saudi Arabia (Fig. 8). Expert spatial models of walkable access, daylighting, and energy were implemented upon the tangible interactive matrix. Tangible pieces represented building typologies with variable density and land use configurations. The tool is designed for planners to coordinate and reconcile competing agendas within the Authority that are a function of land use and density.

Fig. 8. Case study application for urban planning with land use and walkability simulation.

B. Delivery Logistics

Logistics experts used the platform to present parametric models of delivery service areas in a real-time, changeable environment (Fig. 9). Users manipulate tangible objects representing distribution centers and other spatial parameters to change a quantitative evaluation of the logistics network. The model is being developed for both internal deliberation and external presentation.

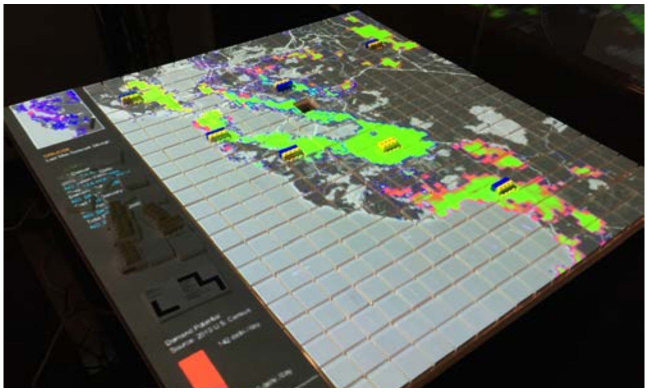

Fig. 9. Case study application for logistics with last-mile delivery optimization.

C. Crisis Resource Management

We deployed the system at a local university in Hamburg, Germany to facilitate a series of community engagement exercises aimed at allocating a recent flood of refugees into the municipality (Fig. 10). Representatives from various districts participated in workshops in which they could receive feedback from the system by manipulating blocks that represent geospatial location of refugee allocations. Performance metrics such as density, land ownership, and strain on public infrastructure were used to assess the feasibility of various refugee allocations. Participants were free to alter allocations dynamically rather than be confined to a single proposal.

Fig. 10. Case study application for allocating refugee housing in Hamburg, Germany.

V. CONCLUSION

In this demonstration we present the tangible interactive matrix system as a low-cost interface for visualizing and manipulating matrix-based algorithms. In case studies of the system, models and analysis that were once trapped in less accessible mediums were revealed to a broad array of users and stakeholders including university students, manufacturers, city planning officials and the general public.

While case studies have revealed a wealth of potential applications, our next steps are to evaluate the performance and effectiveness of tangible interactive matrices in a more controlled manner. Example studies include evaluating the device's impact on group dynamics, learning, teamwork, creativity and user satisfaction with outcomes compared to traditional methods for information display and manipulation such as power point presentations and excel. Future case studies may incorporate models for other fields such as supply chain, factory production, and laboratory environments.

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