DoppelLab: Tools for Exploring and Harnessing Multimodal Sensor Network Data

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***Abstract*— We present DoppelLab, an immersive sensor data browser built on a 3-d game engine. DoppelLab unifies independent sensor networks and data sources within the spatial framework of a building. Animated visualizations and sonifications serve as representations of real-time data within the virtual space.**

I. Introduction

Our environments are increasingly filled with sensor networks designed to provide specific data and solve predetermined problems, but information from embedded sensors remains, for the most part, locked in closed-loop control systems and out of reach of the majority of users. In a technology-driven rush to collect new and ever more streams of information, sensor networks have been deployed so quickly and broadly that users, be they consumers monitoring their personal energy usage or corporations tracking their global supply chains, can barely manage the data influx, much less know how to interpret the data. Rapid developments in sensor networks research are enabling real-time, mobile and distributed sensing, bringing these technologies into new domains, from homes and offices to construction sites, where users might face challenges integrating real-time information into existing practice. At the same time, sensor fusion algorithms that would make sense of these data require *a posteriori* knowledge, which in many cases is lacking or non- existent for new deployments. When models are available, these algorithms tend to reduce data to single dimensions of interpretation, separated from other data streams that may provide valuable context.

Motivated by increasingly dense deployments of disparate sensor networks and an absence of interface tools that can truly span across network-siloed sensor data, we present DoppelLab, a scalable, open-ended platform for creating collocated representations of general sensor network data. This platform supports an audio-visually immersive, 3-d virtual space in which users can explore real-time sensor data and inferences of all types, as well as long-term, aggregated information and knowledge. Building on a game engine, DoppelLab transforms architectural models into browsing environments for real-time sensor data visualization and sonification, proposing to organize these virtual representations by the physical space from which they originate, and thereby enabling both broad and specific queries about the activities, systems, and relationships in a complex, sensor-rich environment. By providing tools for rapid parsing, visualization, and application prototyping that can take advantage of the platform's horizontal relationship to otherwise independent sensor networks, DoppelLab aims to drive new interfaces to data and physical-world actuation.

DoppelLab lets users walk through and interact with sensor data within a building, or fly out of the building to see it buzzing with layers of activity and information. To date, we have incorporated hundreds of building-wide distributed sensors at the MIT Media Lab and other instrumented spaces, and are planning for further deployments. Our visualizations are based on intuitively metaphorical animations and are easily adapted or swapped for different applications, a key consideration in our system design that allows developers to quickly prototype their own visualizations and customize existing ones. We have also begun exploring sonification as a method for increasing user immersion: our system incorporates live, voice-scrambled audio feeds from across the Media Lab complex, and spatializes them in the virtual model. We are planning to mix this audio with abstract sonifications of sensor data, providing a means for users to hear fully 3-d representations of information.

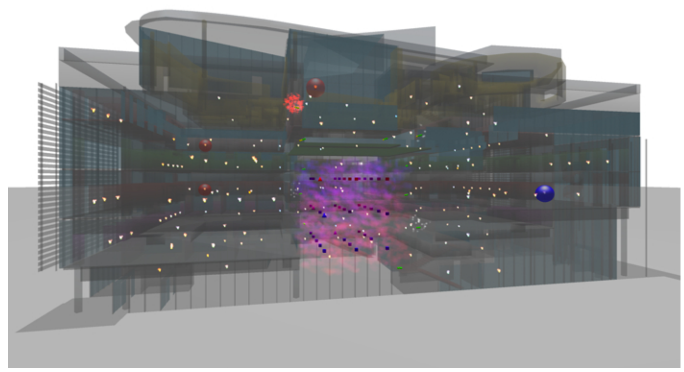

Fig. 1. Translucent view of the MIT Media Lab in DoppelLab.

Intuitively and scalably collocating representations of dense sensor network data presents a significant design challenge. We elucidate these challenges, and draw on visualization design strategies to help solve them. Behind the scenes, our back-end server and database framework collects data from multiple, disparate networks and stores it generically, providing a means for aggregation and analytics that cut across individual sensor networks. More broadly, this paper lays the groundwork for exploratory modes of user interaction with sensor network data. By enabling users to move fluidly between convergent data streams and the higher-level inferences that fuse them together, this work aims to develop interfaces that foster better understanding of sensor-driven context and the data that produce it.

Our work draws on a broad set of fields, including cross-reality, visual analytics, sensor network user interfaces, data sonification, and sensor data management. Sec. II of this paper reviews the relevant literature from these fields, and situates the work within them. Sec. III presents the DoppelLab system, describes the sensor networks, visualizations, and sonifications we have developed, and details the client-side and back-end architectures that constitute the platform. DoppelLab is an ongoing research effort, and Sec. IV briefly outlines our future plans. Sec. V concludes the paper.

II. Related Work

There have been a number of recent efforts to create general-purpose sensor network user interfaces. The Tricorder [1] and Ubicorder [2] are a family of location- and orientation-aware handheld wireless sensor network browsers; the latter provides an interface for defining inference rules. Both systems feature a graphicallyaugmented 2-d floor plan. Other work has focused in particular on user interfaces for defining inference rules on data streams through scripting [3]. A number of commercial enterprises have developed user interfaces to sensor data, for consumer applications like home energy monitoring [4], [5]. These products center on 2-d graphical representations that can become quite complex as networks grow.

Recent efforts to approach this problem theorized cross-reality environments, where ubiquitous sensor networks would interact with pervasively shared virtual worlds [6], [7]. These efforts focused on the point of exchange between physical and virtual environments, and hinged on the concept of massively multiplayer virtual worlds, like Second Life. Many of the challenges faced by this research are particular to that concept of pervasive sharing in virtual worlds, chief among them the vacancy problem, which results from a combination of asynchronous usage and typically low levels of user interest. In contrast, this paper focuses on encouraging and enriching individual users' experiences of sensor data in 3-d environments.

Several other papers explore the use of game engines for information visualization. Brown-Simmons, et al. use game engine affordances to encourage exploration of environmental data and communicate a specific point of view [8], [9]. Kot, et al. apply a game engine to information visualization [10]; but focus on gaming metaphors such as shooting, limiting their scope.

The burgeoning field of visual analytics develops interactive visual interfaces that support analytical reasoning and decision-making. Visual analytic designs aim to to transmit large data sets concisely, enable comparison between multiple streams of information, and encourage user interaction with visualizations [11]. Users choose between modular representations, assess the efficacy of various designs, and aid in the fabrication of new designs [12]. This ease of interaction facilitates feedback workflows from design to inference and back.

DoppelLab incorporates live, spatialized audio streams into the virtual environment. This work has an early precedent in systems like CAVE [13], which created an immersive soundscape by spatializing sounds within a 3-d virtual space. We are beginning to investigate sonification of real-time sensor data streams over a network. In [14], Lodha et al. develop a generative music system based on Western tonal harmony, and emphasize the importance of using a musically pleasing sonification to improve user experience and reduce fatigue. In [15], Hunt and Hermann show the benefits of low-latency, direct-manipulation interfaces in sonification. We address this through client-level spatialization which responds to movement in the virtual space. Other work has shown that pitch-mapping sonifications can be as effective as visualization in conveying properties of functions of one variable [16].

III. DoppelLab

DoppelLab is an immersive, cross-reality virtual environment that serves as an active repository of the multimodal sensor data produced by a building and its inhabitants. Built on the Unity3D game engine, the platform leverages physics and lighting, interactive animations, and other game engine affordances such as distance culling to structure and encourage exploration of the data.

A. Visualizations

In DoppelLab, visual representations of data take the form of metaphorical animations that express absolute and relative magnitudes, rates of change, and higher-level inferences that relate data across time, space, and sensing modalities. Visualizations take place within the walls of the building, corresponding to the physical locations of the sensors, and the walls can be toggled into translucence

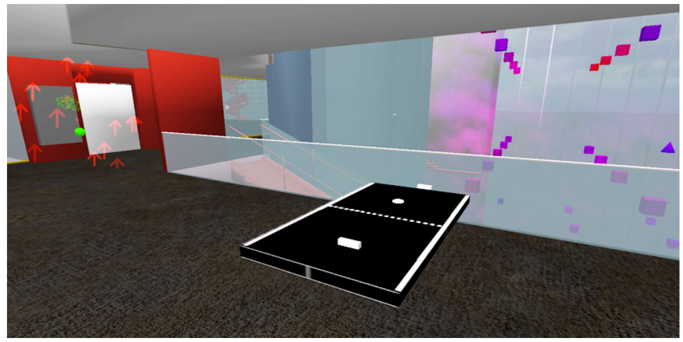

Fig. 2. An instrumented ping pong table is visualized in DoppelLab as a 2-d game of Pong (center). In the background, temperature and humidity measured on a dense grid in the atrium are shown as colored shapes and fog.

to expose the relationships that span across the building. Organizing data in this way provides a largely intuitive platform that emphasizes the relationship between people and their physical environments. While projections and transformations to other spaces can produce more efficient representations of data for many kinds of queries, the physical space serves as a consistent and relatable starting point.

We draw on Edward Tufte's seminal works to identify a number of visual principles that structure our interface design [17]. Adherence to the physical space provides a means for *self-representing scales*, that normalize the size (and relative significance) of any visual cue against the architecture itself. In DoppelLab, a large and fast growing set of data sources poses a visual and interface design challenge. As such, we seek visual representations that engage with users to reveal information and expose functionality in response to their exploration through the virtual space, making the density of information in a representation a function of the user's virtual proximity to it. This notion of *macro and micro design* makes the platform scale to large numbers of data sources and analytical visualizations without overwhelming the user. To the same end, we aim for visualizations that make use of every graphical element to show data; these *multi-functioning elements* consolidate conceptually related sensing modalities into compact forms, using multiple properties of each object or animation.

In its current form, DoppelLab renders data from an increasingly large and dense set of building-wide distributed sensors at the MIT Media Lab complex and one researcher's instrumented living space. Fig. 2 includes a dense network of 45 temperature and humidity sensors suspended in a large atrium represented by nodes whose color represents temperature and shape reflects the rate of change; these nodes are surrounded by foggy clouds of particles that track levels of humidity, where dense, red fog indicates high levels, and blue, sparse fog the opposite. DoppelLab supports multiple visual interpretations of the same data that can be toggled using keyboard modifier keys. Shown in Fig. 3, a system of several hundred thermostats at the Media Lab is represented by flame animations whose colors reflect absolute temperature, and by spheres whose color and size reflect the local deviation of the temperature from the set point; both visualizations highlight anomalously large differences between the two.

DoppelLab connects to a network of distributed sensor nodes carrying motion, temperature, humidity and light sensors, as well as stereo microphones. Some of these nodes are linked to daughter boards with barometric pressure, light color, ozone, volatile organic, and particulate sensors, for monitoring machine shop activity. Coincident audio levels and motion are represented as a set of spheres that accumulate into circle as audio levels increase (resembling a traditional level meter), and undulate as motion increases, combining

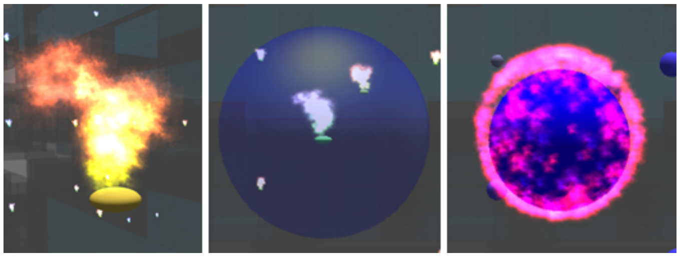

Fig. 3. Thermostats are represented by colored flames (left). An anomaly between the setpoint and measured temperature is indicated by a pulsating sphere (center) and an alternate visualization (right) shows the magnitude of the discrepancy.

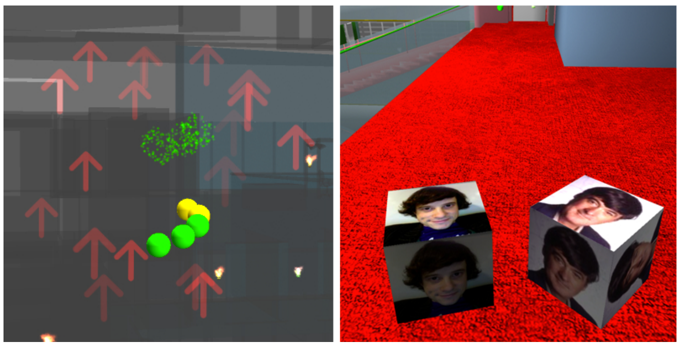

Fig. 4. Social activity visualizations: at left, an audio level-meter ripples with the amount of coincident motion, while the typical levels float overhead; the arrows reflect an unusually high level of social activity that is trending upward. At right, RFID tags are detected and faces are shown.

the two into an indicator of social activity. When a user approaches the visualization, the typical sound and motion levels for the current hour and current day of the week appear for comparison as a ghostly copy of the original. As shown in Fig. 4, when the activity level over the preceding 10 minutes exceeds the typical value by some margin, the visualization spawns a cloud of arrows whose density and orientation reflects the trending social hot-spot. DoppelLab also makes use of an extensive network of RFID readers, showing the faces of people carrying tags as they move through the building. In addition, Twitter messages appear in DoppelLab as they are broadcast, localized to individuals' virtual offices using an institutional directory. The position of a ping pong ball on a sensor-equipped table is shown as a continuous game of 2-d pong (Fig. 2). Finally, DoppelLab incorporates external factors, like the position of the sun, under the assumption that it may impact the HVAC and other systems.

B. *Sonification*

We aim to provide an informative and pleasing data sonification to complement DoppelLab's graphical display. We have designed a tiered architecture for audio processing, spread across sensor nodes, centralized servers, and the client.

The first layer of this architecture performs node-level speech obfuscation, preserving the character of the sound but rendering speech unintelligible to protect privacy. We prototyped two algorithms: the first reverses sequential segments; the second stores 5 recent segments and selects from them randomly. The first has the benefit of leaving sounds slower than speech, including some music, mostly unchanged, and listeners found the output smooth. However, reversing drastically alters transient sounds, and can be easily decoded by an eavesdropper (although randomizing the buffer size could mitigate this problem). The second technique preserves transients, and is significantly harder to decode. However, listeners noted that this algorithm sounded more "busy" and "choppy", and longer structures like sentences were more disrupted. We are presently investigating the potential for granular synthesis to address some of these challenges.

After obfuscation, audio is streamed to a dedicated DSP server, where further data sonification algorithms run. This server supports rapid programming in Max/MSP. On the client, we have designed a custom plugin to download, decode, and spatialize the streams.

C. *Interface*

DoppelLab is built on the Unity game engine, which makes use of Mono, the open-source version of Microsoft's .NET Framework. Scripts are written in C# and UnityScript, a JavaScript-based language. The system is organized hierarchically; centralized scripts deal with server communication and parsing, and pass messages to lower-level scripts that manage visualizations of each network. Centrally, the update loop periodically polls the data server, and the server responds with an XML file containing the requested data. If no data is found for any given sensor, the corresponding animation is disabled. The system relates its coordinate system to the building floorplan, and passes messages and data accordingly; lower-level scripts that manage visualizations and animations use those data to control properties of objects in the environment. These parameters are visualization dependent, and include object properties like color, shape and size, or in the case of particle systems, systemic properties like emission rate and lifetime.

A simple development process is central to our system design, allowing developers to quickly prototype their own visualizations and customize existing ones. The application makes a number of animations "drag-and-drop" ready so that developers need not repeatedly reinvent existing designs, and to produce a certain level of consistency in the user experience. The goal is that DoppelLab support a rapid development-to-visualization-to-development cycle, whereby visualizations suggest relationships and correspondences to users, and the environment enables on-the-spot prototyping of new applications. One such application, designed for building managers, reveals anomalies in the thermostat data–specifically, large deviations from the local set point. This idea came about because a visualization of absolute temperatures showed what appeared to be strongly correlated and unusually high temperatures in a series of adjacent rooms; significantly, the result exposed a previously unknown fault in the building HVAC system.

In addition to streaming in real-time, data are also stored, aggregated, and analyzed on the server, enabling users to speed through weeks or months of data in minutes. We created two preliminary interfaces to this functionality on the client side, supporting a simple (exploration) mode and an advanced mode. The exploration mode, shown in Fig. 5, is modeled on video editing timelines, where the top slider sets the system time within a 24 hour range, and the bottom slider moves that range across a span of days and months. Data can be played back at 4 different time scales–real-time, 1 minute per second, 10 minutes per second, and 1 hour per second. The sliders advance with the time, together with an analog clock. The advanced mode supports input of specific times into a text box.

D. *Server and Database Architecture*

The data used by DoppelLab is generated by multiple independent networks. The DoppelLab architecture includes a server that brings together data from these independent networks, storing it in an SQL database. This provides the client access to both current and historical sensor data from many different sensor networks in a generic format.

Fig. 5. Interface for exploring historical sensor data.

The database distinguishes between two types of sensor data, *samples* and *events*. *Samples* are numeric values produced by a sensor at regular intervals, and are stored as a triplet of a unique sensor ID, a timestamp, and the numeric value. *Events* occur irregularly, and might contain larger amounts of data; for example, the appearance of a tag (with an associated username) at an RFID reader, or a message posted to a Twitter feed, are both stored as timestamped events.

Metadata about each sensor is also stored in the database, including the sensor's type and location. Sensors are organized into logical groups to facilitate higher-level queries: a thermostat, for example, has both a temperature sensor and a setpoint, and a node in a sensor network might have a collection of various sensors. We are also beginning to implement facilities for sensors with changing locations, where the location of a sensor is itself a sensed value.

Scripts on the server periodically request the data from each data source and store the values in a generic format in an SQL database. Simultaneously, the server also computes hourly averages which are cached in a separate table. This aggregation permits fast execution of queries over longer timescales, such as 'What is the average reading on this sensor at 3 PM on Mondays?', or 'What days of the week tend to have the highest average motion activity at noon?'

The DoppelLab client accesses the data stored on the server via HTTP requests, which allow queries for aggregate data over time intervals ranging from one second to ten minutes, and over hours.

IV. Future Work

DoppelLab is evolving quickly as we add sensors and features, as well as new buildings and environments, including our own instrumented living spaces. We are integrating real-time data from wearable devices and fine-grained location systems, as well as distributed video. As we deploy interfaces in new built environments, we have begun testing the system with facilities managers, who have found DoppelLab's spatial organization of sensor data particularly useful for tracking the state of building systems.

Our hierarchical and modular system simplifies the design and development process for visualizations and sonifications, as well as back-end analytics. An extension of our efforts to facilitate rapid deployment of new interfaces is the design of a markup language that will codify and further streamline this process.

Sonification in the DoppelLab environment is very much a work-in-progress. We are exploring the use of generative music techniques to encode further data in our sonification, in addition to spatialized audio recordings. For example, by applying resonant filters to the audio streams, we can differentiate the streams from one another, while also mapping new data parameters to the cutoff frequencies of the filters. Finally, we are beginning an arts residency with a composer, and hope to draw on his musical experience in our design.

V. Conclusion

Motivated by the increasing availability of real-time data and few means for users to explore these layers of information, we developed DoppelLab, a comprehensive browsing interface that enables exploration across independent sensor networks and data streams. DoppelLab is an open-ended and intuitive environment that transforms data into interactive visual and auditory experiences, aiming to foster better understanding of sensor data and their relationships across space, time, and modality. We see this work leading to a transformative moment in ubiquitous computing, where interfaces and applications built atop distributed sensor streams intimately connect people to the rapidly emerging Internet of real-time data.

More information about DoppelLab can be found in [18], and an interactive web player is available at http://doppellab.media.mit.edu.

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