Microbiology Tray and Pipette Tracking as a Proactive Tangible User Interface

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Abstract. Many work environments can benefit from integrated computing devices to provide information to users, record users' actions, and prompt users about the next steps to take in a procedure. We focus on the cell biology laboratory, where previous work on the Labscape project has provided a framework to organize experiment plans and store data. Currently developed sensor systems allow amount and type of materials used in experiments to be recorded. This paper focuses on providing the last piece: determining where the materials are deposited. Using a camera and projector setup over a lab bench, vision techniques allow a specially marked well tray and pipette to be located in real time with enough precision to determine which well the pipette tip is over. Using the projector, the tray can be augmented with relevant information, such as the next operation to be performed, or the contents of the tray. Without changing the biologist's work practice, it is possible to record the physical interactions and provide easily available status and advice to the user. Preliminary user feedback suggests this system would indeed be a useful addition to the laboratory environment.

1 Introduction

Many work environments can benefit from integrating computing devices so that they can provide users with important information where and when they need it. In addition, keeping track of what users are doing can enable proactive applications that automatically record actions for later analysis or prompt users about the next steps to take in a procedure. Of course, automatically discerning the many actions users may perform can be a daunting task for an automated system. Fortunately, the structure of most work environments helps to make this a tractable problem.

Our work focuses on augmenting the cell biology laboratory [1]. Biologists perform their tasks at a collection of specialized work areas. Each work area has specialized equipment and material and is usually dedicated to one particular task. Our experience is with the laboratories of University of Washington's Cell Systems Initiative with whom we collaborate on this work [2]. There, we have identified 8 different tasks and their corresponding work areas, including centrifuging, incubation, titration and dispensing, thermocycling, etc. In this paper, we highlight our work related to the tasks that involve the dispensing of

liquid into well trays. Well trays are a convenient array of small containers, each holding a different combination of reagents and cellular material. Some steps in the experiments act on an entire array at once (e.g., incubation) to generate data for different values of reagent parameters.

Figure 1 shows an outline of an experiment plan that highlights the tasks that involve mixing liquids in the well trays. The tool being used is TeraLab, a product of TeraNode [3], a commercialization of the Labscape tools we previously presented at this conference [4]. TeraLab captures an experiment plan (the icons on the left represent the eight different types of steps) and associated parameters (type of material, amounts, links to images, etc.). The experiment plan of Figure 1 shows the cross-products of materials that are dispensed and mixed into the containers of the well trays. Note the vertical and horizontal arrangements to generate all possible combinations of materials. An expanded view of some of this detail is shown in Figure 2.

However, there are many more details missing from this experiment plan. When a biologist is at a workbench dispensing materials into the well trays (see figure 3), he is likely to be working on only one of many experiments. Therefore, we need a way of identifying the tray so that it can be connected with its corresponding experiment. We also need a way to know which materials are being dispensed and how much material is being pipetted into a particular well in the tray. The trays have a coordinate system that helps biologists keep track of what material they put where, but they must jot this information down on a piece of paper or on the tray itself. This is a common source of errors or ambiguities when the experiment is written up later as many shortcuts and abbreviations leave room for interpretation. In addition, the process of recording this information on paper distracts the biologist from the flow of the procedure. Interpretation is further complicated because the notes tend to be incomplete. In some cases it is not even possible to take notes since paper is not permitted in certain parts of the laboratories because it can be a contamination agent.

We seek to make this recording process automatic through the use of a variety of sensors that can capture the important aspects of the biologist's activities. To this end, we have developed a method for attaching RFID tags to reagent bottles and their lids. An antenna embedded in the workbench can be used to sense which bottle has been lifted, whether its cap has been removed and when it has been replaced, and when the bottle is returned to its original location [5]. We have also instrumented a pipette to wirelessly transmit its aspiration and dispensation events and report the quantity of liquid drawn or dropped [6]. This paper reports on the missing piece of automating this workbench, namely, determining into which well the liquid was dropped. In addition, we help the user keep track of what was placed in each well.

We present a video tracking system that tracks the well tray and pipette. It can precisely determine over which well the pipette tip is placed by the user. Correlating this with pipette events and movement of reagent bottles allows us to keep track of how much and what type of liquid was dispensed into a particular well in a particular tray. This information is used to annotate the

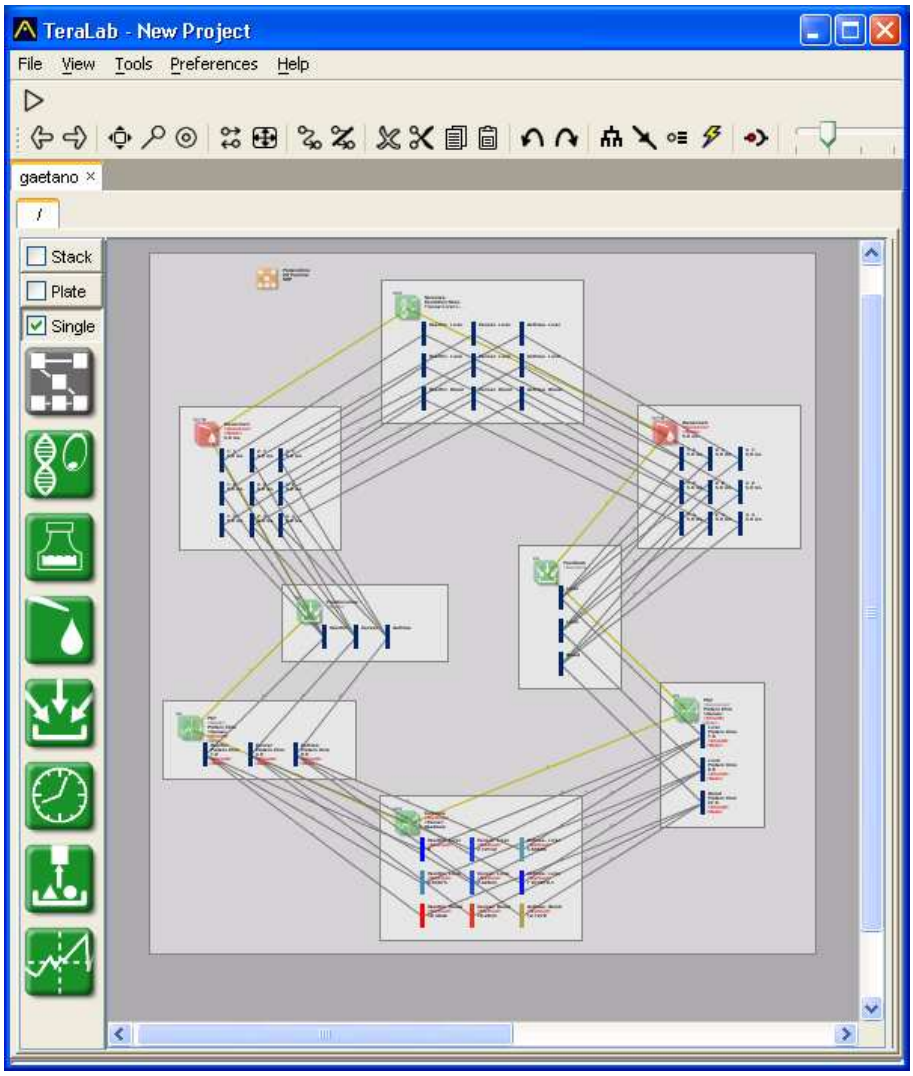

Fig. 1. Overview of a portion of a biology experiment expressed in TeraLab (Teranode).

TeraLab experiment plan and allow the user interface to continuously display to the biologist which steps have been completed and which are left to be done. Furthermore, we can project the contents of the well directly onto the workbench (immediately above the well tray) by using a projector set up in parallel with the video camera. The projector can also provide information about which well to dispense into next and generally aid the biologist in keeping track of their work even through interruptions. To make the tracking algorithm robust, we color-code the edges of the tray and the shaft of the pipette (but not its disposable tip, which we can precisely position by extrapolation).

We believe this work to be a novel application of tangible user interfaces. We have made the well tray and pipette into I/O devices for the computers supporting this activity. Most importantly, we have augmented an already established procedure and require little or no adaptation on the part of the biologist. Their processes are not altered and the computing is invisibly inserted into the laboratory without causing undue distraction. Information is presented in situ and the objects of the work itself are used as input (well tray ID and position of pipette tip) and output devices (well tray location and contents projected onto the workbench surface).

In the following section, we will review related work. In section 3 we will discuss design and implementation of both the vision tracking system and the augmenting display. We will then present some analysis of our system, including feedback from our target user group, and wrap up with future work and conclusions.

2 Related Work

There is a variety of previous work that share some similar aspects with our project. These break down into two categories that follow the two main components of our system: augmented reality, where extra information is displayed onto existing surfaces, and physical interactions, where physical objects are used to interact with a computer.

Everywhere Displays [7, 8] are steerable projectors that allow interfaces to be projected onto surfaces all around a room. A paired camera allows the system to notice occlusions and move the display and to look for user interactions with the display. Although some uses of the Everywhere Displays involve displaying environment relevant information, the main focus is to allow the computer display to be moved from its fixed location on the desktop and to allow the user to interact with the virtual objects in the display using fingertip tracking. There are also several other systems that use a projector to display an interface and a video camera to track interactions, often using hands or fingers. For example, FingerPaint [9] tracks fingertip location to be used in a drawing program, and EnhancedMovie [10] is a video editing system that allows the use of both hands to manipulate video clips. These systems all allow interaction with virtual objects using hands as pointing devices without involving other physical objects. Augmented Surfaces [11] use visually unique tags on physical objects to give

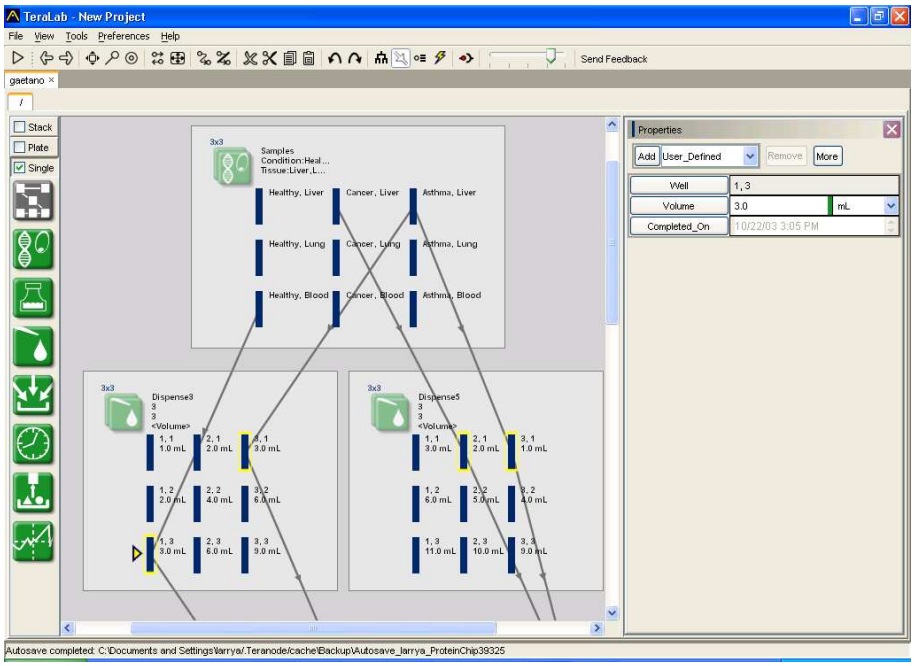

Fig. 2. Detail view of a TeraLab dispensing step. (not all dependencies shown)

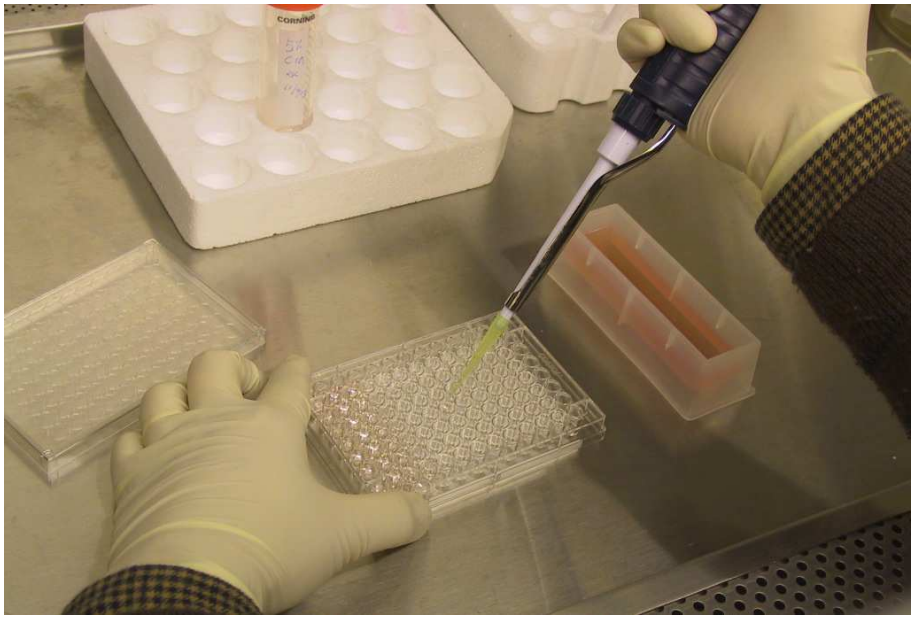

Fig. 3. A laboratory environment where a microbiology experiment is being conducted.

them presence in a shared virtual display, extending interactions beyond the computer screen. Although the setup and techniques of this system are similar to ours, the goal is quite different, providing extended display or allowing access to virtual objects by physical association. In contrast, our system does not try to make virtual objects available for interaction. Instead it tracks interactions between physical objects used in an existing task and augments the environment with information about those physical objects.

There are also systems that focus on using physical interactions with objects as direct input to the system. These Tangible User Interfaces often try to attach virtual devices or abstract concepts to physical objects. Tangible Bits [12] and the metaDESK [13] take the standard desktop environment and convert some familiar components into physical versions, which can be directly interacted with. BUILD-IT [14] is an example of merging virtual and physical interactions in a so-called Natural User Interface, where users collaborate on a design by interacting with physical blocks. SiteView [15] allows users to create rules about their environment by manipulating physical representations of the rule components. All these systems try to give a physical representation to interfaces that are currently virtual. We take the opposite approach, and attach virtual associations to an existing physical environment.

Work that has been done on merging augmenting displays with physical interaction tracking is closest in spirit to our own. One well known example of this is the DigitalDesk [16] which blurs the line between physical and electronic documents. Using a camera and projector system similar to our own, it tracks a user's interaction with paper documents and can provide augmented services on top of the traditional interactions. In an idea similar to the Double-DigitalDesk [16], Tele-Graffiti [17] tracks paper interactions to allow remote collaboration through a sketching interface. Total Recall [18] captures whiteboard annotations which can later be rewound to be viewed in-place or on a separate display. The Designers' Outpost [19] captures existing site design practice in post-it note and whiteboard sketch form to support enhancements like remote collaboration, versioning, and extended information. Work on the Augmented Reality Toolkit [20] has created a variety of augmented reality applications using special tags to locate objects in relation to a camera and display information on them [21]. These projects and our work all share a similar goal of taking an existing task and enhancing it by augmenting the environment based on the actions that take place. However, they are all in very different domains and have different forms of interaction. In particular, a distinguishing feature of the laboratory domain is that an experiment plan (see figure 1) is often known before the experiment is performed. This important characteristic allows our system to proactively suggest actions and flag errors, something that is not available in the above mentioned systems.

3 Design and Implementation

3.1 Overview

Our system is composed of several components to handle display of information and sensing of objects using familiar computer vision techniques. Our physical setup (see figure 4) consists of a projector and camera mounted above a workspace, similar to many other systems. A semi-automated calibration routine computes a homography between the camera and projector image spaces, giving the system the ability to locate an object in the camera and project information about it onto the matching physical benchtop location. Our implementation currently looks for 96-well trays (8 by 12 array of wells) and a 100 microliter pipette. In order to identify and locate these, we have marked them with patterns of bright colors (see figure 5). Processing the colors and patterns gives us location and orientation of the objects, which can then be augmented with the projector display. The next subsections will detail the normal processing path of our system.

3.2 Color Segmentation

The use of brightly colored tags allows us to separate the markings from the rest of the image, making it easier to process the patterns by first performing color segmentation (see figure 6B). We are primarily interested in the hue of the color rather than the luminance of it, as the latter is easily influenced by lighting conditions. Following previous work [22], we convert from the camera's RGB color space to an HVC color space. This allows us to classify a color based on its hue. Furthermore, we take into account the color's saturation level (chroma), and filter out extreme luminances (value) because very bright or very dark regions often have poor color information. In order to run this as quickly as possible, we create a lookup table to directly map RGB values to their color segment, as has been done for robot vision [23]. We spent considerable effort choosing colors that the camera could pick up well, and we were able to hand-tune the results of semi-automatic color calibration in order to get more robust segmentation. These calibration steps should only be needed once per installation and do not need to be done by the users.

3.3 Grouping Pixels

Once each pixel is classified into a color segment, the next step is to group pixels into larger units. Connected components are found by looking in the neighborhood of a pixel for pixels of the same color and grouping them into one component. Each marking on an object should be found as one component. Although it is common to blur the image to smooth out connected regions, we found our results sufficient even without blurring. Regions are also filtered for size and shape, so that very small and very large regions that do not match expected ranges for our markers are ignored. These steps help filter out clutter that may be caused

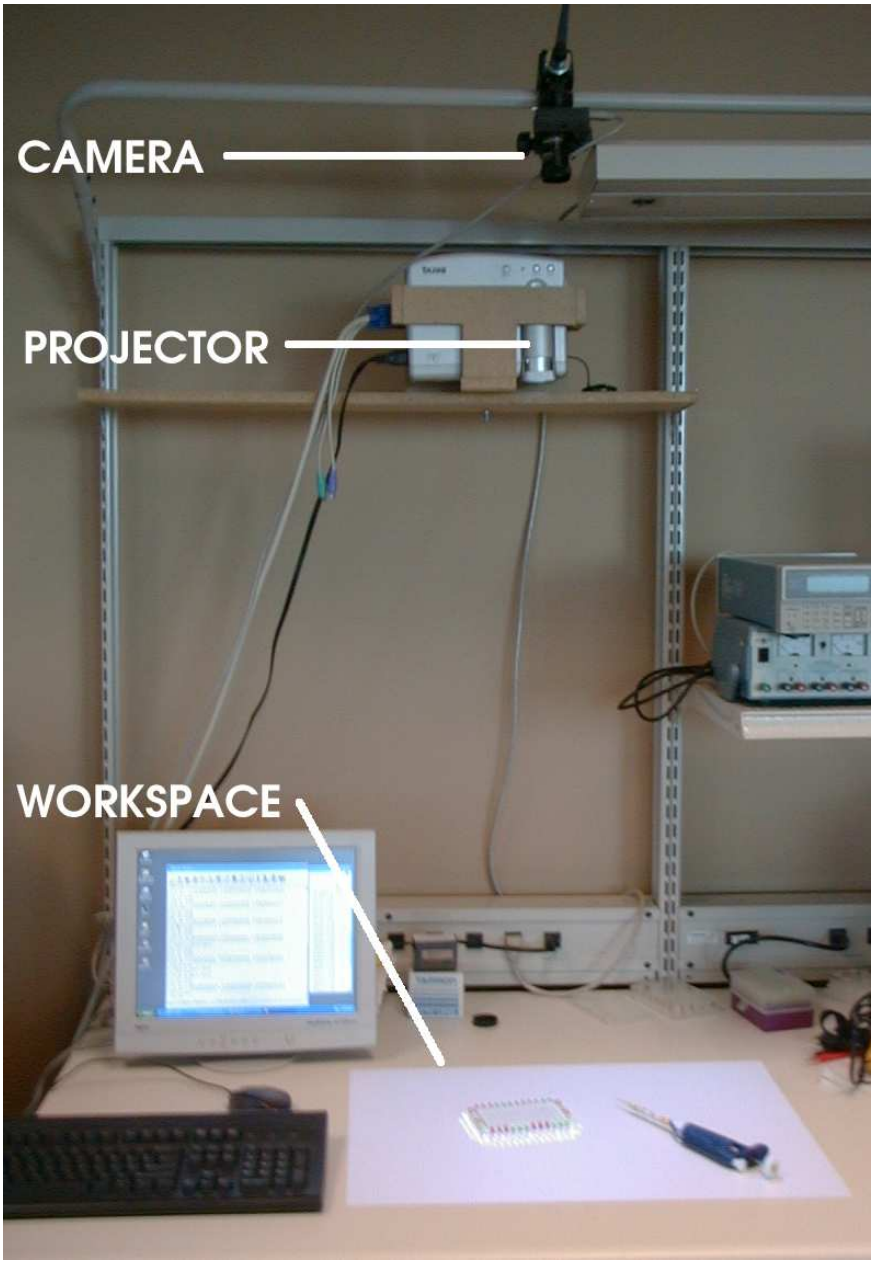

Fig. 4. Our setup with a camera and projector above the workbench. The camera tracks the tray and pipette, and the projector allows us to augment the tray with information.

by other items in the workspace. For example, even if the container in figure 3 matches a marker color, it will not cause confusion because its size and pattern do not match known profiles. Once these connected regions are found, they are organized into linear groups. At first, we used a Hough transform to find lines at different angles through the image and locate what components were along this line. This was relatively slow, so we switched to a direct method that fits a line to a group of components. More specifically, line segments are fit to the three closest neighboring components, and approximately collinear segments are clustered into groups. Then a single line is fit in a least-squares sense through all components in the group.

3.4 Recognizing Tray Patterns

Once lines are detected from the previous step, we first create a list of tray candidates by looking for groups of 4 lines that form a rectangle of an aspect ratio close to that of the tray (see figure 6C). To handle partial occlusions, we also consider groups of 2 or 3 lines that may form part of such a rectangle. Allowing a little margin for the angles between the sides and the aspect ratio enables us to detect the tray even when it is tilted out of the plane.

We then validate each tray candidate by matching the colors of components along each side with the actual patterns on the tray. The patterns are designed in a way that enables us to uniquely identify individual marks within the tray coordinate system, given sufficient number of visible marks. The marks are laid out with a regular spacing in alternating colors to indicate orientation and the origin of the tray coordinates (see figure 5). Also note that our marking system does not interfere with the standard form factors or usage models of the tray.

To see if a tray candidate matches the patterns, we first calculate an estimate of the inter-mark spacing for each side using the side's length, the expected number of marks, and the median of the spacings between neighboring components. If the entire side is missing, we borrow the spacing estimate from the other sides. Using the estimated spacing, we then assign each component to its corresponding mark on the patterns in all possible orientations of the tray. Finally, we compare the average color of each component with that of the assigned mark. All tray candidates that match the patterns are considered a valid tray.

The tray can be located even in the presence of considerable occlusion. We are able to detect the tray with at least parts of two sides visible (with sufficient number of marks to distinguish the sides and locate the marks within each side), and within a reasonable range of tilt that covers typical usage.

3.5 Locating Pipette Tip

The disposable tips used on the pipettes are transparent because laboratory workers need to be able to see liquid pulled into the pipette. Because of this, we could not put opaque markings directly on the tip of the pipette. Instead, we use a simple technique to determine the location of the tip in relation to the body of the pipette. A set of regularly spaced markings allow us to locate the body, and

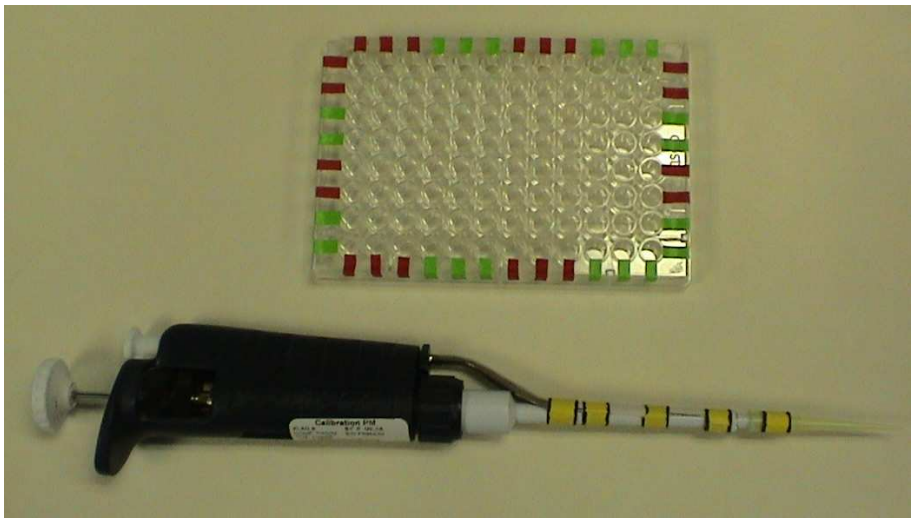

Fig. 5. Red, green, and yellow markings used on tray and pipette.

one marking at a different spacing allows us to determine the orientation (the handle end versus the tip end). Once the locations of the points and direction of the pipette is found, the tip can be located by using the spacing between the markings. In our setup (see figure 5), the tip is two spacing-widths away from the closest mark; this ratio holds even as the pipette is tilted out of the plane. Since there are fewer marks than on the tray, there is less redundancy and locating the pipette is not as robust to missing markers; the pipette tip can be located with one missing marker, as long as it is not the marker that determines orientation (see figure 6F). The pipette tip is located within a few pixels of the true location. This precision is on the same scale as the radius of the wells on the tray.

3.6 Interface Display

Once the tray and pipette are located in the camera image, this information is displayed back to the user directly on the work surface. The camera space is transformed into the projector space using a previously computed homography, so that projected elements land in the correct location. A simple homography is suitable because the tray and pipette are only used very near the surface of the table. A box is displayed around the tray, with the rows and columns labeled, to give acknowledgement that the tray has been located, and a red circle is drawn at the pipette tip. When the location of the pipette tip corresponds with the location of a well in the tray, the row and column labels are highlighted and the well is marked with crosshairs. This allows the user to easily and peripherally determine that an interaction is recognized correctly. If the user hovers the tip over the well for about a second, an information bubble about the well pops up, displaying its history. This currently only includes a list of the times at which

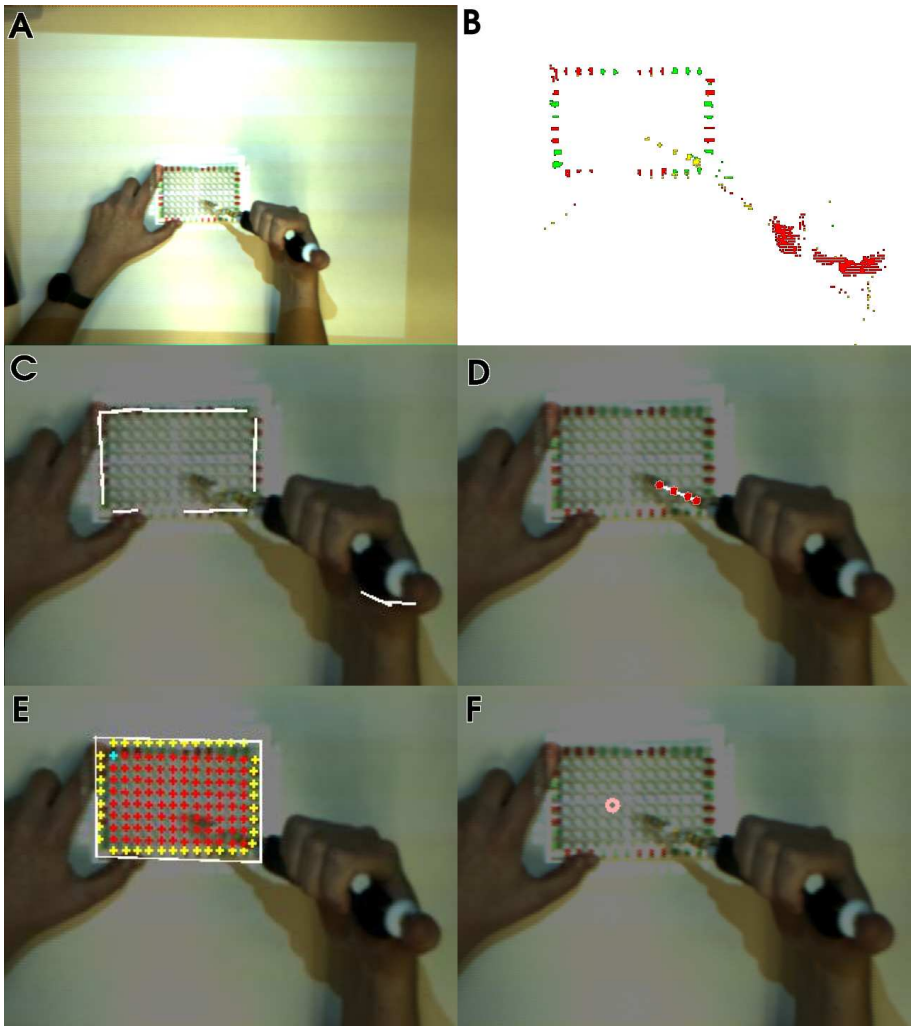

Fig. 6. The steps involved in locating a tray and pipette. A: the full view as seen from the overhead camera. B: the color segmentation of the relevant portion of the image. C: candidate lines for a tray location. D: candidate lines and marker points for a pipette. E: a located tray, showing well location and origin. F: a located pipette tip.

material was added to the well, but integration with other systems should let us record what the material was and how much of it was added, as well as display the future planned contents of the well.

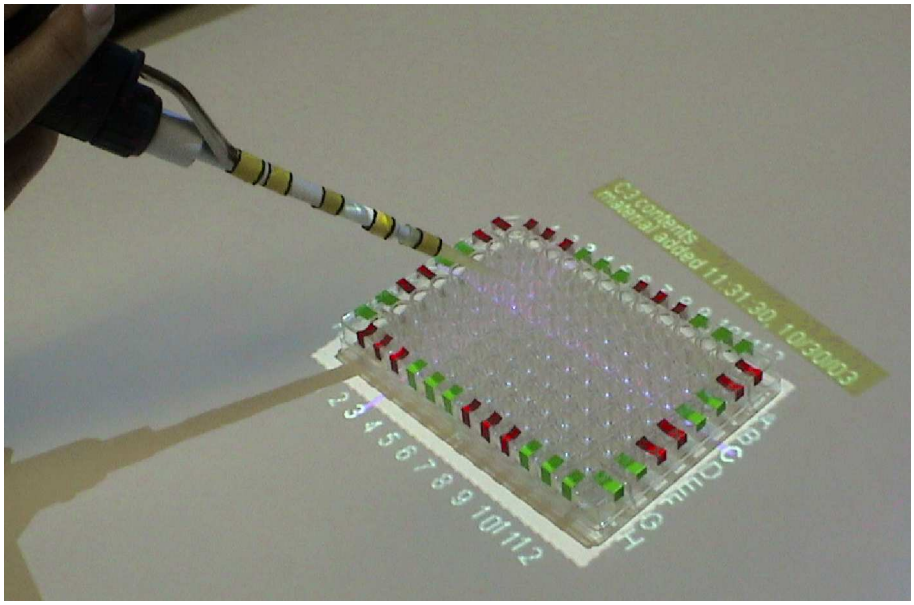

Fig. 7. Display reacting to pipette and tray. Note how the coordinate system of the tray is recognized and displayed, and how the pipette location is highlighted. Information about the selected well is displayed above the tray.

4 Analysis

Our image processing and user interface is implemented in Java, with input from a firewire camera running at 640 by 480 resolution. This setup can run at about 4 frames per second, but a surprising amount of time is spent displaying the interface. With the interface turned off, just running the image processing components, the system runs at 11 frames per second. Using an optimized Java virtual machine, or switching languages, would likely boost the system speed. With unobstructed views of the tray and pipette, the tray is found about 99% of the time, and the pipette about 95% of the time. The source of errors in these cases seems to be color variations in images retrieved from the camera. Our location routines are strict enough that false positives are very infrequent, and false negatives could be smoothed out to present a more stable interface to the user.

We asked three of our collaborators at University of Washington's Cell Systems Initiative [2] to test out the system. They are all experienced laboratory workers (not computer scientists), and are the target audience for our application. However, as members of our team they have an interest in seeing the application in daily lab use and are not the harshest critics. We invited them to get familiar with the system by performing tasks similar to those used in their own experiments, and to give us their opinions of the system and how it would fit with their lab practices. Each session lasted approximately one hour. This preliminary evaluation generated useful feedback, which will be discussed here.

During development and testing, we were using the pipette as a new pointing device, rather than a tool to move liquid. Because of this, we were holding the pipette in significantly different ways than would be done in the lab. Our participants told us it is necessary to make sure the liquid makes it into the well, and does not stay clinging to the pipette because of surface tension; this means the pipette tip is often brought into contact with the bottom or the side of a well. In order to touch the bottom of the well, the pipette must be held at a steep angle, often causing the camera's view of markings on the pipette to be obstructed. We originally chose to put the camera directly overhead to minimize distortion, but it is now clear that this will not work given the standard laboratory practice. Since most of the operations are in the plane of the benchtop, it should not be problematic to change the camera angle to give a clearer view of the pipette. Having the pipette tip in contact with the edge of a well occasionally confused the selected well with its neighbor, since the tip was now close to the center of both. This could be helped by the location algorithm suggesting a point slightly in from the tip, instead of the very tip of the pipette. Some simple experiments could tell us what part of the pipette was in the center of the well for the average use case.

Despite the problems caused by obscuring the camera view of the pipette, all of our participants were able to quickly adapt their technique to one that allowed the system to locate the pipette. Their updated technique was performed at approximately the same speed as their original. The visual feedback from the system also gave users awareness that their action had been recognized, and our users reported that the display was not distracting with regard to carrying out the experiment. To confirm the usefulness of feedback, we had our participants transfer liquid to the tray with and without feedback. Without the feedback, there was no indication that the location of the pipette had been correctly recorded for a dispensing event. With the feedback enabled, the users got a view into the state of the system so they could tell when a location was recognized and would be correctly recorded. This knowledge allowed them to adjust accordingly, usually in subtle ways or simply by waiting for acknowledgement of recognition. We found that feedback made a drastic difference; in one case, when our subject was not provided with feedback, 14 of 16 locations for dispensing events were not found, compared to only one of 16 not found with the feedback enabled. Our system was also able to keep up with our participants' motion, even though it was only running at 4 frames per second.

All of our participants felt that this system would be useful in their lab environment. Even in its current state, they felt that it would help them keep track of what operations they had done, and help them recover from interruptions. They indicated that a secondary display that could show them the status of all wells in a single view (see figure 8), would make it easier for them to find where they left off, rather than having to hover over each well to query its contents. They also liked the idea of using proactive prompting to show them which operation and which well should come next, or flag them with warnings if they were poised to deposit liquid into the wrong well. They also confirmed that they could save time if their actions were documented automatically as they did them, instead of having to manually record their process on paper, and then later transfer it back to a computer.

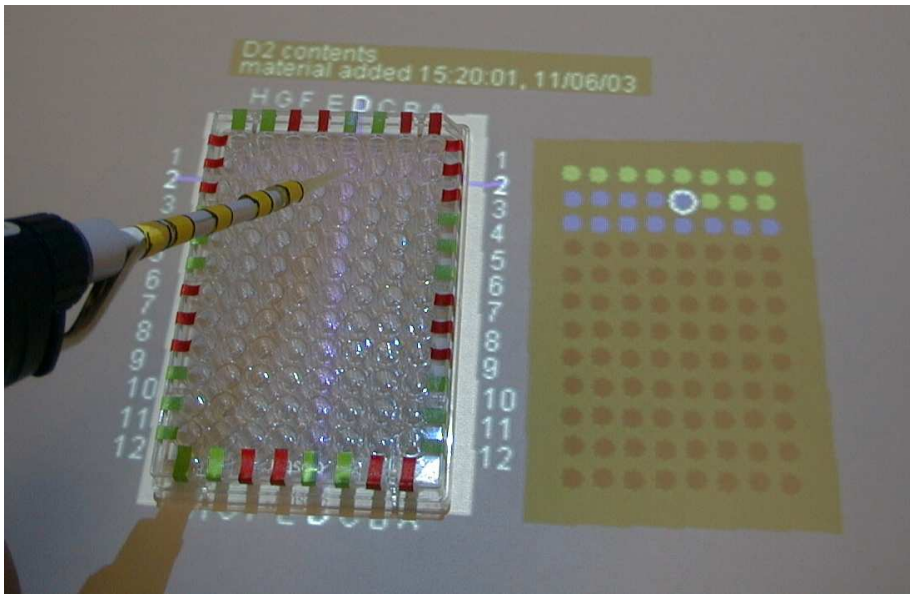

Fig. 8. Another potential view of information about the well tray. The display on the right of the tray shows an abstract status of all wells, with detailed information still available by selecting a single well.

5 Future Work

We feel that there are several areas of future work: integration with TeraLab, incorporating more sensors, improving speed and robustness, and in-depth user studies. Some of these possibilities are discussed in more detail in the following paragraphs.

Integrating the experiment plans of TeraLab (see figure 1) with our system will provide much more information for the user interface. The display will then be able to indicate the next step to a user, or alert the user if their actions do not match with the expected steps. TeraLab's recording facilities will allow transparent storage of all the actions performed on each tray directly alongside the experiment procedure: for later recall and tracking, for use in formal write-ups, or for sharing.

Use of additional sensors will allow us to record more information and associations with the experimental data. RFID tags on the trays would allow us to uniquely identify trays and pull up their stored history for display. Tagging reagent containers would also provide information about what was dispensed. Conversations with the lab workers helped us to identify some difficulties in extending the system in these ways. They told us they often bring many reagents to the table at once, and they often put them in intermediate containers before they deposit them into the wells. They also sometimes hold the container they are dispensing from in their hand, rather than leaving it at a fixed location on the table. This means a simple RFID system to tell which reagent is at the bench is insufficient, and the camera may even be unable to find a consistent location for the source. However, biologists are trained to never open more than one bottle at a time to minimize contamination risks (a better structured environment than medication use, where similar RFID systems have been proposed [5]). We believed that determining the last opened reagent in a structured workflow such as this can be quite accurate in determining the reagent in use. In more complicated cases where reagents are mixed or diluted, a known experiment plan can be very helpful in telling the system what to expect, and minimal user prompting can be used where necessary.

We are also aware that some experiments involve transferring material from one tray to another, and while our vision system can find separate trays, it cannot distinguish between them. An RFID reader would be able to report the presence of multiple trays, but not location. However, using multiple RFID antennas could provide a finer location resolution to help associate identification with a visual location of a tray. The merging of these two systems could provide accurate identity and location information, similar to systems used for people tracking [24]. We might also consider a visually based unique tagging system like CyberCode [25] to identify and locate trays. If occlusions of the pipette markings continue to be a problem, a system like Mimio [26] with an added direction sensor may be a possibility for resolving pipette location. We also plan to investigate using multiple cameras to improve accuracy; multiple views would help with occlusion and glare problems. A small camera mounted on the pipette could give a more detailed view of the tray, and thus a more accurate location for the pipette tip in relation to the tray. Additionally, there are different types of pipettes (of different volumes and with different sized tips or multiple tips) that should be trackable using the techniques discussed, but they will need to have unique features so they can be distinguished from each other. Different tray

sizes can easily be accomodated using RFID tags to include size, aspect ratio, and well diameter information.

Although our participants were able to use our system, we feel that faster and more robust tracking would improve the experience. We expect the speed of our system can be improved considerably by switching computing platforms and through further optimization. As mentioned, the use of multiple cameras may give better accuracy and robustness. We may also explore different markings besides color, perhaps infrared, or rely more on pattern than on color. More temporal information could also be included in our system to help improve reliability. It may be beneficial to incorporate uncertainty into our framework too, so the accuracy of the system can be taken into account when reasoning about events. For example, a threshhold can be set for when prompting is necessary, or a known experiment plan and user habits can provide prior knowledge of where to expect a pipette tip.

We would like to conduct further user studies in a real laboratory environment with users that are not part of our group. By asking users to perform common experiments in a realistic setting, we could study how our system influences work patterns. The use of different information displays could be studied to determine what was best suited for a given task. Creating a configurable information display would allow different displays to automatically be shown for different tasks or user preference. It would also be valuable to find what level of user prompting was acceptable and sufficient.

6 Conclusion

We have built a vision-based system for tracking the interactions between microbiology well trays and pipettes in a laboratory environment. The preliminary evaluation and feedback from our target users indicate that we have built the beginnings of a useful system. Using the projector to provide feedback allowed the users to readily adapt to the limitations of our system. We believe that improving the frame rate and adapting the camera setup for typical lab use will make our system more robust. We also think a more developed user interface will improve the usefulness of the system. There is still considerable integration necessary before the system can actually be deployed in a lab. Most importantly, we need to connect to the Teralab experiment plan and data recording facilities to allow the actions performed in the experiment to be automaticalled recorded and saved. A scheme to determine what reagents are being used is also necessary, and will likely be based on a combination of sensors and interactively prompting the user.

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References

1. Arnstein, L., Hung, C.Y., Franza, R., Zhou, Q.H., Borriello, G., Consolvo, S., Su, J.: Labscape: A smart environment for the cell biology laboratory. Pervasive Computing Magazine **1** (2002) 13–21
2. http://csi.washington.edu: University of Washington CSI website (2003)
3. http://www.teranode.com: TeraNode website (2003)
4. Arnstein, L., Grimm, R., Hung, C.Y., Kang, J.H., LaMarca, A., Look, G., Sigurdsson, S.B., Su, J., Borriello, G.: Systems support for ubiquitous computing: A case study of two implementations of labscape. In: Pervasive Computing Conference. (2002)
5. Fishkin, K., Wang, M.: A flexible, low-overhead ubiquitous system for medication monitoring. In: Intel Research Technical Report 03-011. (2003)
6. Arnstein, L., Sigdursson, S., Franza, B.: Ubiquitous computing in the biology laboratory. Journal of Lab Automation **6** (2001)
7. Kjeldsen, R., Levas, A., Pinhanez, C.: Dynamically reconfigurable vision-based user interfaces. In: 3rd International Conference on Computer Vision Systems. (2003) 323–332
8. Pinhanez, C.: The everywhere displays projector: A device to create ubiquitous graphical interfaces. In: Ubiquitous Computing (UbiComp03). (2003)
9. Crowley, J.L., Coutaz, J.: Vision for man machine interaction. In: EHCI. (1995) 28–45
10. Ishii, Y., Nakanishi, Y., Koike, H., Oka, K., Sato, Y.: Enhancedmovie: Movie editing on an augmented desk. In: Ubiquitous Computing (UbiComp03). (2003)
11. Rekimoto, J., Saitoh, M.: Augmented surfaces: a spatially continuous work space for hybrid computing environments. In: Proceedings of the SIGCHI conference on Human factors in computing systems, ACM Press (1999) 378–385
12. Ishii, H., Ullmer, B.: Tangible bits: Towards seamless interfaces between people, bits and atoms. In: CHI. (1997) 234–241
13. Ullmer, B., Ishii, H.: The metadesk: Models and prototypes for tangible user interfaces. In: ACM Symposium on User Interface Software and Technology. (1997) 223–232
14. Fjeld, M., Bichsel, M., Rauterberg, M.: BUILD-IT: An intuitive design tool based on direct object manipulation. Lecture Notes in Computer Science **1371** (1998)
15. Beckmann, C., Dey, A.K.: Siteview: Tangibly programming active environments with predictive visualization. In: Intel Research Tech Report 03-019. (2003)
16. Wellner, P.: Interacting with paper on the DigitalDesk. Communications of the ACM **36** (1993) 86–97
17. Takao, N., Shi, J., Baker, S.: Tele-graffiti: A camera-projector based remote sketching system with hand-based user interface and automatic session summarization. In: International Journal of Computer Vision. Volume 53. (2003)
18. Sanneblad, J., Holmquist, L.E.: Total recall: In-place viewing of captured whiteboard annotations. In: Ubiquitous Computing (UbiComp03). (2003)

19. Klemmer, S.R., Newman, M.W., Farrell, R., Bilezikjian, M., Landay, J.A.: The designers' outpost: a tangible interface for collaborative web site. In: Proceedings of the 14th annual ACM symposium on User interface software and technology, ACM Press (2001) 1–10
20. http://www.hitl.washington.edu/artoolkit: ARToolkit website (2003)
21. Billinghurst, M., Kato, H.: Collaborative augmented reality. Communications of the ACM **45** (2002) 64–70
22. Gong, Y.: Detection of regions matching specified chromatic features. Computer Vision and Image Understanding **61** (1995) 263–269
23. Jamzad, M., Sadjad, B.S., Mirrokni, V.S., Kazemi, M., Chitsaz, H., Heydarnoori, A., Hajiaghai, M.T., Chiniforooshan, E.: A fast vision system for middle size robots in robocup. In: RoboCup Symposium. (2001)
24. Schulz, D., Fox, D., Hightower, J.: People tracking with anonymous and id-sensors using rao-blackwellised particle filters. In: IJCAI. (2003)
25. Rekimoto, J., Ayatsuka, Y.: Cybercode: Designing augmented reality environments with visual tags. In: Proceedings of DARE. (2000)
26. http://www.mimio.com: Virtual Ink Mimio website (2003)