# Cover Page

**Title of submission:** The LIGA Traveler: The Use of Social and Technical Invariants in Software Design

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# The LIGA Traveler: The Use of Technical and Social Invariants in Software Design

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## Abstract

It is not enough for software to support individual interactions well. Designers must consider the broader community's experience across the entire system life cycle. People involved in the program's use, maintenance and management must experience it and its designers as behaving meaningfully, intuitively and responsively – in short, as situated in their community.

This paper discusses the design of an information management tool for micro-mechanical systems fabrication. The LIGA Traveler serves a specialized, R&D community at Sandia National Laboratories. Supporting this community required we understand both the pressures for change within it, and the technical and social invariants that counter those pressures. This paper discusses the process of interpreting field data to discover these invariants, and how we used them as a foundation for the design of the Traveler system. It presents a set of software components we have built specifically to support our design process.

## Keywords

Ethnographic methods, Information Architecture, Interaction Design, Participatory Design, Human-Centered Design, User-Centered Design.

## Industry/category

Engineering Research and Development.

## Project statement

We belong to a software group at Sandia National Laboratories in New Mexico that builds software to support engineering research and development. In recent years, Sandia has been developing practical applications of micro-mechanical fabrication methods. One of these is a lithographic fabrication process called LIGA, which can produce metal parts with a feature resolution on the order of 10 microns. Currently, LIGA is making the transition from R & D to a practical manufacturing technology. Defining stable fabrication processes requires recording and analysis of data on both successful and failed lots within the research environment that characterizes LIGA fabrication.

Although space prohibits an in depth discussion of LIGA, a brief description of the process is necessary to understanding the problem. LIGA is an acronym of the German words for Lithography, Electroplating and Molding. Figure 1 illustrates the LIGA Process, along with a LIGA part beside a common penny.

The first step sandwiches a PMMA (Plexiglass) sheet between a silicon substrate and a gold mask. Openings in the mask define the part shape. Exposure to high energy X-rays (2) breaks up the polymers in the PMMA where they are not protected by the mask, and development (3) in various chemicals removes the exposed PMMA. Electroplating (4) deposits metal into the openings in the PMMA mold, and planarization (5) smoothes the top of the metal. The final step dissolves the PMMA and (6) releases the parts

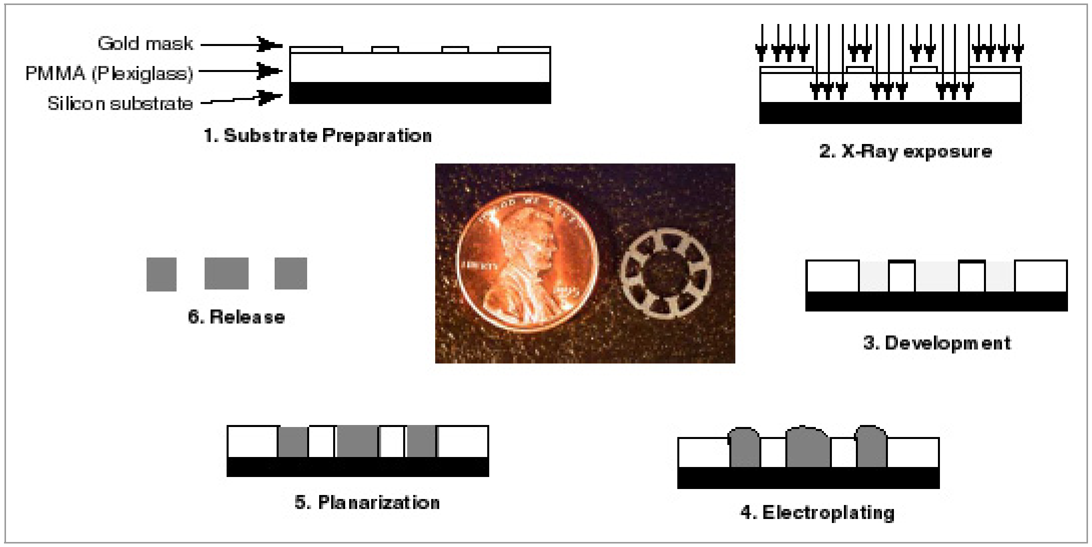


Figure 1

The tool we built to gather data on this process, called the LIGA Traveler, is a distributed Java application that is installed on user machines (both PCs and Macs) using a web-based distribution tool called Web-Start. These applications communicate with a central server and database. The LIGA Traveler allows people to examine all fabrication lots currently in process, to search archives of old travelers, and to create new travelers for different fabrication processes. Within a single traveler, we designed a number of specialized tools to simplify data entry, and to allow people to navigate the processes with maximum flexibility.

The LIGA Traveler bears a superficial resemblance to the traditional manufacturing traveler: a set of paper or electronic documents that follow a fabrication lot through its manufacture, allowing people to record data on various stages of the process. However, because LIGA is still under development, it lacks the well-defined structure found in mature manufacturing technologies. It is not uncommon for LIGA engineers to adjust their processes "on the fly" in response to problems, novel part designs, new materials, etc. At least two earlier efforts failed to be adopted because they lacked the flexibility our customers required.

Although on the surface the LIGA Traveler is a simple data entry and management program, it differed from earlier attempts in three ways: 1) We took advantage of invariants in the structure of LIGA technology and the user community to guide interaction and user interface design. 2) Our software architecture supported these invariant structures, making it simple for us to modify the system in response to changes in their processes. 3) We have continued to remain closely involved with our user community.

## Project participants

The core development team is small, consisting of three designer/developers. We are all trained in computer science, and have experience ranging from a few years to several decades. All members of the team have experience in user-oriented design, fieldwork and prototyping methods. There are no specialists on the team: everyone is involved in all aspects of systems design, from fieldwork to user interfaces to system architecture. We have worked together on a number of projects, and collaborate efficiently and intuitively.

One of the most important qualities of this team is our long history (5-7 years) writing software for Sandia's mechanical engineering and materials science communities. More recently, we have been working with micro-mechanical systems R&D at Sandia, and have spent the last several years doing small projects and fieldwork with a variety of micro-mechanical systems technologies and applications. This broad knowledge of Sandia's micro-mechanical systems community was a major contributor to our success.

Owing to the range of technologies involved in LIGA, our user community is a somewhat loose combination of people with diverse science and engineering backgrounds, including chemists, materials scientists, manufacturing engineers, electroplating specialists, part designers and process engineers. This diversity was a major constraint on our design work.

Sandia's culture is an important factor in all our design work. As an engineering laboratory devoted to high consequence weapon systems, Sandia has evolved an intense culture of personal and organizational responsibility. This is typical of innovative communities, where it is difficult to impose processes or software from outside the organization. Although we have long been committed to participatory design, we view it more as a matter of our participating in their community, than of bringing users into our design process.

## Project dates and duration

We started fieldwork in winter of 2001. This was part of a broad effort aimed at all micro-mechanical systems technologies at the labs, but one focus of our effort quickly became the LIGA Fabrication group at Sandia Laboratories in California. After initial fieldwork, we built a screen-only prototype of the system, which we showed to the LIGA group, securing their support. We delivered the first working version of the system in winter of 2002. The system is currently being used, and we remain involved with the LIGA community.

## Process

Our design process draws heavily on elements of design ethnography, participatory design [1], and rapid prototyping. We follow a pragmatic approach that is shaped by the problems at hand, by our relationship with our users and our understanding of their technology, and by the current state of the design. However, several themes are common to all our work.

- We spend much more time doing fieldwork in the user community than is common to rapid prototyping methods like eXtreme Programming [2]. We believe that systematic fieldwork is more effective at finding the deeper structural invariants in a user community than evaluations of software prototypes, which tend to focus on more superficial questions of function and usability. Prototypes are more useful in the later stages of refining and validating designs.
- Interaction design [3] is the central focus of our development cycle, since it is the link between people's goals and activities, and the system's behavior. Based on our fieldwork, we develop a set of scenarios: informal, narrative descriptions of instances of interaction with our proposed system. These scenarios drive the design of screens, system architecture and data structures.
- Our approach to fieldwork emphasizes the interpretation of observations over particular ethnographic methods [4]. Our methods – interviews, observations, focus groups, and prototype evaluations – are typical of empirical design methods. What is of interest are the interpretive patterns we use to find structural invariants in the user community.

As mentioned earlier, we had been working with Sandia's broader micro-mechanical systems community for about a year when we decided to focus on LIGA fabrication. We made this decision because LIGA was the closest to being used in real systems, and had the most pressing needs. We started with background research into the technology itself, including literature searches and fieldwork with Sandia's LIGA community (engineers, materials scientists, simulation modelers, process engineers). Although these people did not belong to our immediate user community, they did help us to understand the context of their work. Early visits to the LIGA group in California focused on their processes, the organization of their laboratories, and the dependencies between different specialties in the LIGA group. We also worked during these visits to establish good working relationships with our user community.

An early focus of our research was on previous efforts to implement a traveler system, and the reasons they did not succeed. One of these was an electronic traveler that users rejected as being "clunky and hard to use." We examined this system, which was designed as a general framework for supporting any manufacturing process: users constructed process-specific travelers by selecting data items from menus and arranging them on a page. Although it accomplished this task well, its generality prevented it from taking advantage of the unique semantics of a given process to simplify navigation, communication and data entry. The usability problems were not simply matters of screen layout, but reflected fundamental commitments in the program's internal architecture and behavior.

The second prior effort was a retreat to paper travelers: forms that would follow part lots through the process. This failed for two main reasons: 1) People didn't always take the time to manage the paper in the casual yet high-pressure atmosphere of a research laboratory. Consequently the forms often failed to be where they were needed and people had to search for them. 2) As paper documents, they did not support the kind of search and analysis needed to exploit the data.

In addition, our customers briefly considered using FactoryWorks, a commercial Manufacturing Execution System. They quickly rejected this option because the strength of FactoryWorks is in process control – making sure all manufacturing conformed to clearly-defined process specifications. This made it less flexible than our users needed.

Design work began with visits to the California site to understand the organization of the LIGA fabrication laboratory. LIGA fabrication is done in different laboratories spread around a large complex of buildings. We spent time in each lab, interviewing the engineers and having them show us how they worked, the tools they used, the problems they faced and the people with whom they interacted. Although time prevented us from doing a full ethnographic study of their work, we did draw on several techniques for interpreting field data, most notably Distributed Cognition [5]. D-Cog analyses collaborative work by focusing on the representations and tools people use to create and share information, and on people's use of those artifacts. Examples of things we examined included paper documents, the organization of files and directories on people's computers, the layout and proximity of the labs, and the handling of LIGA wafers.

Because we live in New Mexico, and the LIGA group is in California, we could not work with them as often as we would like, and had to manage our visits carefully. We generally timed our trips to coincide with the LIGA team's working meetings, so we could observe interactions among the group as a whole. We also analyzed the paper travelers in depth: they were a good specification of the data our users wanted to track. Based on this work, we developed a "screen only" prototype of the system using a set of Java tools for prototyping data-intensive, interactive applications that we had developed on an earlier project. These screens became the focus of user evaluations began building the system in earnest. Also, we continued with our fieldwork, both to gain a deeper understanding, and to support our relationship with the user community.

The small size of the LIGA community allowed us to talk with everyone in it. This is obviously an incredible advantage for the development team, although there is little to suggest our methods would not work as well when limited to samples of a larger community.

One of the most important decisions we made was to delay arriving at a single, unified view of the problem and system requirements, but to take time to explore the different points of view, the conflicting goals and histories, technical specialties, and even inter-personal dynamics in the user community. In our experience, this suspension of decisions is unusual for software projects, which are often driven to define a set of requirements, so people can start coding.

In trying to gain this deeper understanding of the traveler problem and its context, we paid considerable attention to the stories users tell us about their work, goals and community. Currently, there is much interest in the software design community in narrative methods. Approaches include use-cases [6], scenario-based design [7], and the user-stories of eXtreme Programming [2]. One thing all of these have in common is their emphasis on narrative descriptions of people's interaction with the proposed system. Although we also made use of these system stories in the form of scenarios and storyboards, we distinguished them from the informal stories users told us about their work and community. As will be discussed in the solution details, we found these stories to be valuable clues to the deeper structure of the user community.

Because of the LIGA fabrication group's difficult history with automation efforts, we decided not to deliver a prototype as early as many rapid prototyping methods suggest. Instead, we took a more conservative approach of working simultaneously on refining the screen-only prototypes with members of the user community, while developing the database, network security, and server side software to complete the system. We also continued with our fieldwork through most of the design process.

We delivered a working prototype after about eight months, and entered a fairly long cycle of refining and extending it. This included both usability refinements, and adding data items. At one point, the LIGA group added an entirely new material set using SU-8 plastic for the mold material. This had a slightly different process, and required an additional traveler. The architecture of our software, made this fairly simple: we were able to use most of the screens from the basic traveler without changes.

The traveler has now been in use for about a year, and we continue to modify it in response to requests for added features. We also continue to maintain a close relationship with the user community, through frequent phone calls and visits. Currently, our main focus is on designing tools for the fabrication group's customers: the engineers who design LIGA components. We are designing these tools on the foundation of the LIGA travelers, giving the component engineers their own unique views of the fabrication histories of the parts they designed.

## Solution details

The Traveler system was tailored to our user community, as well as the specific processes of LIGA fabrication. This can be seen in the design of the top-level screens, which used the semantics of the fabrication process to simplify navigation, an emphasis on flexibility in process control and data entry, the automation of common practices within each fabrication step, and accessibility by the entire team.

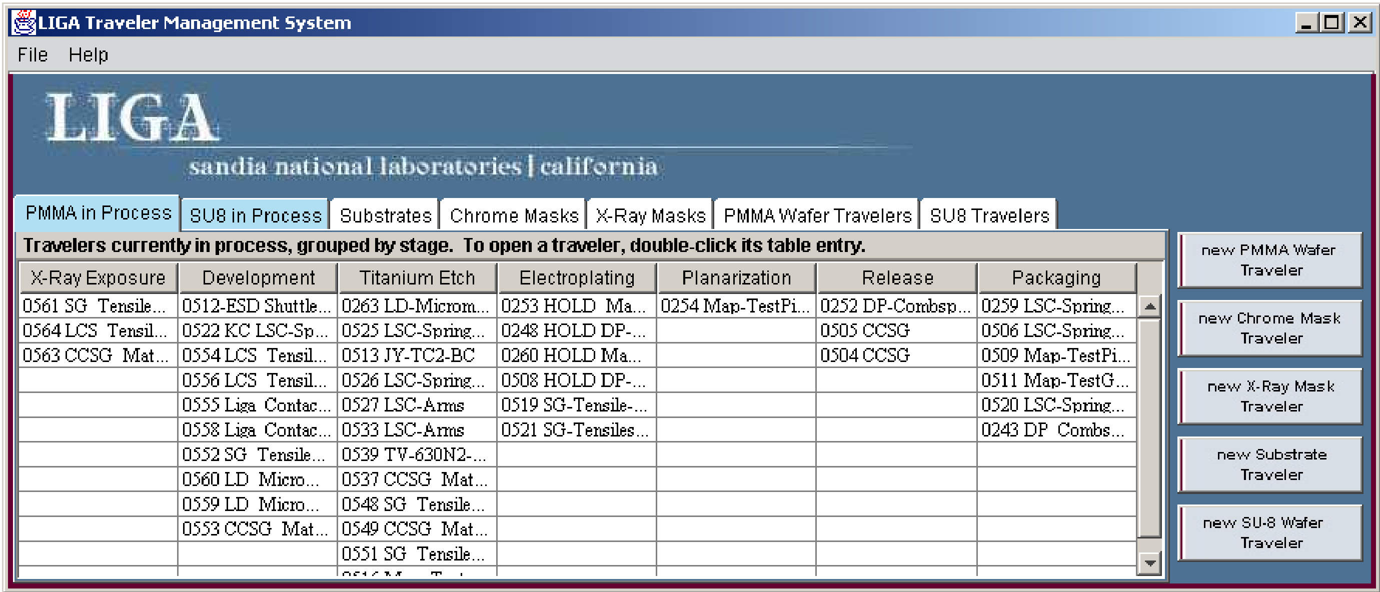


Figure 2

Figure 2 shows the initial screen for work-in-process and archived Travelers. The work-in-process screens took the form of tables in which each column displays all lots in each processing stage for each PMMA or SU8 Traveler.

We designed these screens following observations of the fabrication team's weekly meetings. Each Tuesday morning, the LIGA department manager would build a spreadsheet on his laptop computer showing all the wafers in fabrication, and project it on a screen in the meeting room. Each column of the spreadsheet listed all parts at a given stage of processing. These Tuesday meetings focused on filling in this spreadsheet and discussing any problems that occurred in processing. Because the manual construction of this spreadsheet was time consuming, we decided that building it from travelers in the system should be a priority for our design. This helped both management and users by shortening the Tuesday meeting, and by giving everyone an immediate benefit for keeping their travelers up to date. The additional tab-panes in the top-level panel contain Traveler archives for each capability (Chrome Mask, X-Ray Mask, Substrate, PMMA and SU8 processing). The archives allow users to scroll through lists of all stored Travelers. The ability to sort these potentially long lists on serial number, date of creation or stage of processing gave users a simple form of search.

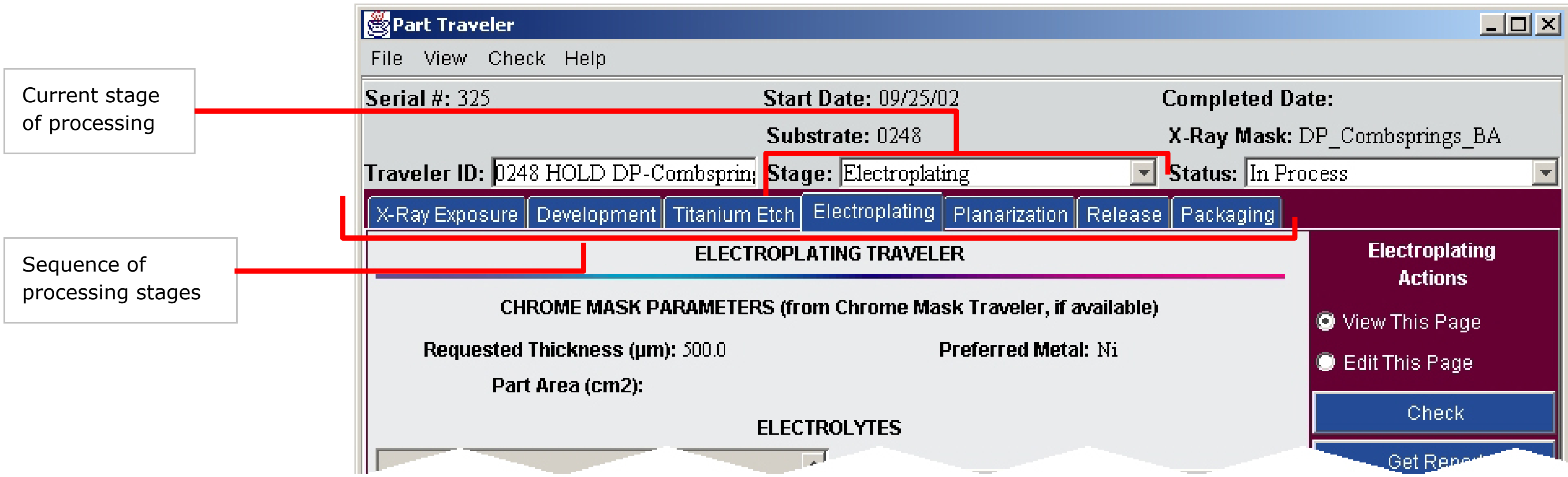


Figure 3

Simple navigation through the system was a primary design goal. In addition to the work-in-process and archives, the users need to view and edit different processing steps (described above) within individual Travelers. Each processing step has a single page on the traveler, and is accessible by the click of a tab pane, as shown in Figure 3. Any supporting Traveler (masks and substrates) may be displayed by a button click within the current page.

We view design as an interpretive process. By this, we mean that the primary focus of design is on interpreting requirements, fieldwork data, casual conversations and reactions to prototypes in order to find their deeper, invariant structure. By invariants, we mean aspects of the user community that remain structurally consistent through time. Basing all aspects of system structure, from interaction design, to user interfaces, to system architecture, on these invariants is a powerful way of insuring usability, robustness, and maintainability.

Our use of the spreadsheet layout of in-progress travelers for the top-level screen illustrates the way we used social invariants in our design work. Because of the technical demands of LIGA fabrication, individual engineers often focus on their own problems and can loose sight of the team's broader goals. The stories people told us underscored this problem. Early on, both the LIGA team's manager and our own instincts stressed the goal of using our software to unify the community and their processes. Coyne [8] has shown that these "unity narratives" are a common way people think about the goals of automation, and also a source of unrealistic expectations. As our fieldwork continued, we detected another very different set of stories in our interviews with individuals. These followed a pattern we nicknamed the "hero story:" each person stressed his or her own role and struggles in bringing LIGA to maturity. These stories revealed a number of deeply rooted conflicts in the community, such as the effect of errors or delays on "downstream" process steps, or the conflict in levels of formality between engineers with manufacturing experience and more research-oriented members of the team. These differences in point of view were so deeply rooted in the community as to be practical invariants – we had little chance of changing these attitudes. However, as is almost always the case with communities of practice [9], the LIGA group had developed its own methods of dealing with these differences. The Tuesday meeting was an equally deeply rooted way the community handled these conflicts: it was where they came together to share their experiences, get an overview of their projects and plan for the future. Designing the top-level screen explicitly to support the Tuesday meeting exploited these invariant properties of the community in the tool's behavior.

The organization of the screens by the major stages of the lithographic process reflected another such invariant. Because our users, as an R&D community, would need frequent changes to the system, we wanted to organize the interface and software architecture around the most stable parts of the process. Consequently, we chose the basic structure of LIGA as a lithographic process (mask creation, exposure, development, plating/molding) to organize screens, even though some process steps could have been logically decomposed even further. For example, the planarization step first takes the electroplated parts and grinds them to a flat surface and then polishes the top of the metal. From a process standpoint, this could be regarded as two steps: grinding and polishing. Our organization combined them in a single Planarization screen. Taking the basic structure of the technology, rather than specific process steps, as our organizing principal proved highly stable in light of requested changes.

The way we chose to track a fabrication lot's movement through processing stages is another example of the sometimes-odd patterns of stability we found in the user community. On the surface, this is a classic workflow problem. However, conventional workflow management software emphasizes control of the process, and does not allow backtracking, skipping steps or other behaviors that might lead to omissions or inconsistencies in the data. For the management of mature manufacturing processes with groups of people who see their jobs as keeping the process on track, this is a viable approach, but we inferred that our users would not accept this level of control, due to both the flexibility required of R & D, and the culture of independence and individual responsibility common to research engineers. This is not a shortcoming of the LIGA group, but is typical of innovative organizations.

Instead, we chose a more flexible scheme for tracking the fabrication process. Each stage of the LIGA process has its own page in the traveler. Tabs at the top of the frame (Figure 3) allowed people to select the page corresponding to their own step. When a user completed a page and saved the traveler, we advanced the traveler stage to match the most advanced page that had been saved. In addition, users could manually change the traveler stage. This supported the uncommon but still possible situation where a wafer was sent back to an earlier stage for additional work.

This approach would have been unacceptable in a workflow system. However, in the climate of an R&D lab, a more rigid approach would have simply caused the entire system to collapse each time someone failed to enter his or her data. This is what happened with the first traveler effort, leading to the perception of its unsuitability. Our approach relied on people's sense of individual responsibility and social constraints to accomplish this instead. If an individual failed to record their data, those downstream were not inconvenienced: they could skip his page and enter their data. However, by recording which pages were omitted, we made it possible for pressure from peers and management to be brought on those individuals to use the system. In this "good cop/bad cop" fashion, we supported a behavior change in the R&D group while avoiding the perception that our software was rigid or aimed at robbing engineers of their autonomy. Essentially, we relied on social invariants in the LIGA community to regulate use of the traveler system.

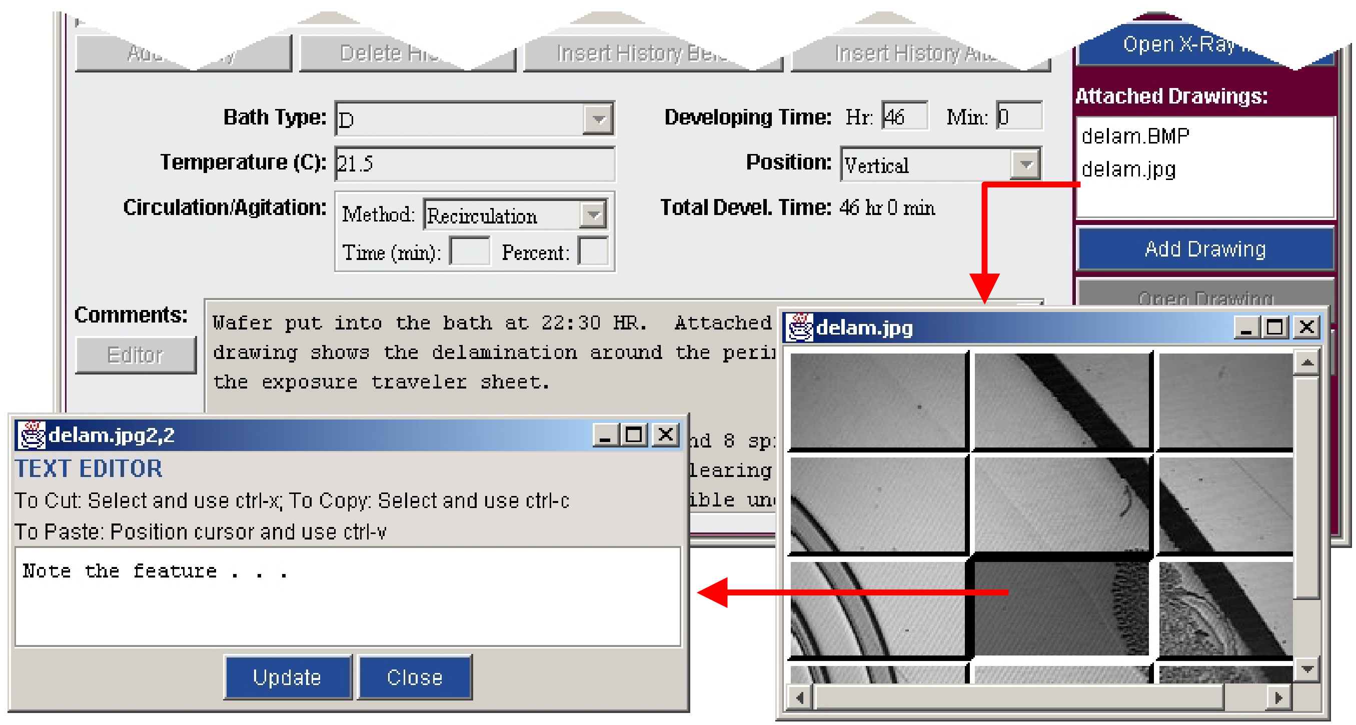


Figure 4

Taking time to achieve a deeper understanding of the user community also kept us from building an overly general tool like the prior traveler system. Many of the stable patterns of work and information we found were unique to a given technical specialty. For example, the organization of information about wafer development does not generalize to other steps. Consequently, each screen of the traveler was tailored to that specialty. This customization touched on everything from the arrangement of screen components, to the choice of units for data, to the use of default values. It also led us to create a number of novel screen components. One of these was an annotated image map (Figure 4), which allowed engineers to attach an image to any traveler and add comments to specific regions of it.

Although originally inspired by individuals who worked with graphic representations of LIGA wafers, it later proved useful for attaching photos of problems in processing and became a very popular feature.

Another example of a custom interaction technique is the use of dynamic tables for those activities that require an indeterminate number of processing steps, depending on circumstances. Although seldom seen in process control systems (where the number of steps is fixed), this was important to our users. We used an extension of Java tables to allow users to enter steps dynamically, and select a row of the table to be edited in the space below (Figure 5). As will be described later, a single object defines all table behaviors.

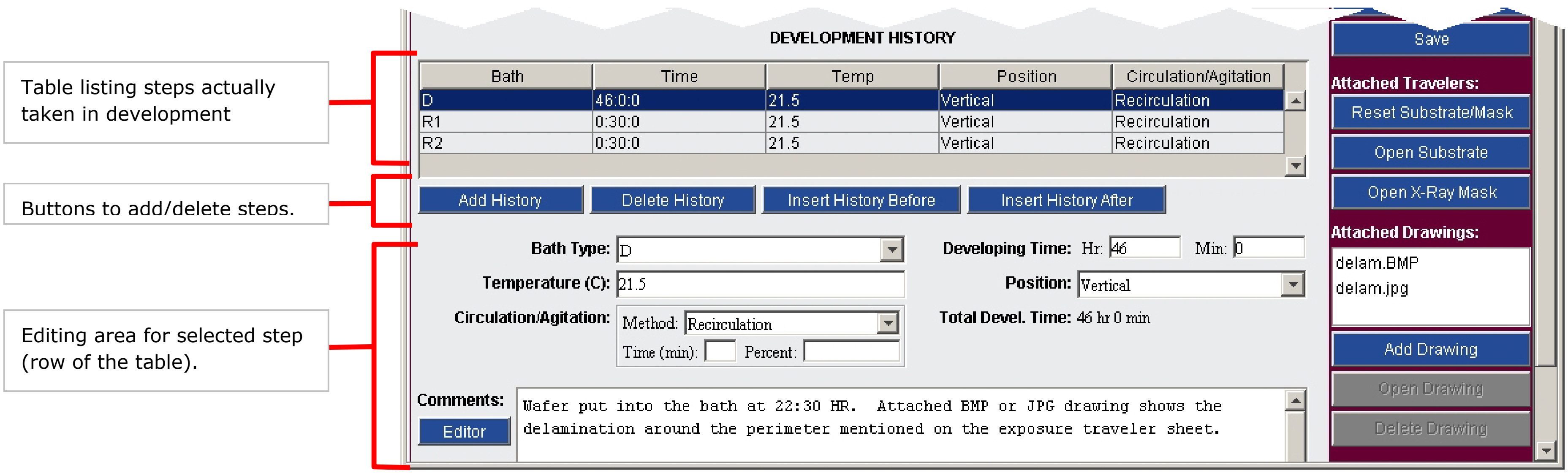


Figure 5

All data in the Traveler system is protected by access controls, although it is visible to all members of the team. This contrasts with more conventional Manufacturing Execution Systems, which often restrict the visibility of information to only that demanded to perform a single step of the process. We also had to provide secure access to the Travelers, on Sandia's internal restricted network, from external computers to accommodate Sandia Labs employees on travel, limited-term foreign nationals working at the labs, and off-site contractors.

*The Information Management Architecture*
As with most prototyping methods, our success depends upon being able to respond quickly to user evaluations and requests for changes to the software. This leads to our belief that the user experience, design methods and software architecture are all deeply intertwined. Also, our view of interaction design as central to the development process leads logically to software architectures that organize the program around the structure of interactions. The basis of the LIGA Traveler's architecture and implementation is a general Java classes called the **Information Management Architecture**.

In practice, the interface code of many computer programs is organized around the layout of components (buttons, text boxes, etc.) on the screen. Behaviors are implemented as event handlers that are attached to the individual screen component objects. So, each button "contains" code to handle button clicks, text boxes "contain" code to handle data entry, etc. The primary structuring principle of the LIGA Traveler user interfaces is the maintenance of a distinct layer of explicitly represented program behavior. Figure 6 gives the system architecture.

The Traveler is a distributed application. A set of Java Servlets and SQL Server Database manage data and interactions from a server. Each client machine runs a Java application that communicates with the server using the common http protocol. The client software is a Java application that defines the Traveler's user interface. This is constructed in three distinct layers: the display layer (1) defines the screen components, their size, color and position. The interaction monitors (2) define the behavior. They listen for screen events such as button clicks, and modify the data held in a set of attribute objects (3).

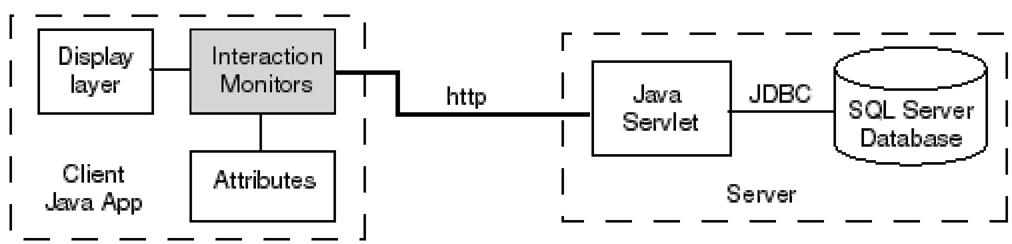


Figure 6

This vertical separation of behavior from both the data and display is complemented by the system's "horizontal" grouping of components, interaction monitors and attributes. Each attribute or set of related attributes is coupled to a small number (usually one) of interaction monitors and related screen components. This simplifies adding or removing data items.

The Information Management Architecture supported our design process in several ways. The interaction layer integrated complex behaviors involving multiple screen components under control of single Java objects. For example, the table of editable items (Figure 5) and the annotated images (Figure 4) were both implemented using a single class. This simplified construction and maintenance of the code. It also let us create very rich screen prototypes quickly by assembling them from components in the Information Management Architecture. These prototypes included our dynamic tables, images, etc. and are much richer than those built using plain Java, html, JavaScript and similar prototyping tools.

What is most important is that the interaction layer classes allowed us to think about system architecture and implementation in terms of behaviors, rather than programming language specific constructs. This gave a close coupling between interaction design and software implementation that helped both in the original construction and the maintenance of the tool. The flexibility of this architecture, when combined with the interpretive techniques we brought to design, helped us to work toward our goal of creating a design process and product our users would think of as part of the fabric of their own work – as situated in their community.

## Results

Our evaluation of our results is informal, consisting of verbal feedback from various users and stakeholders. Perhaps the most important feedback is simply that the LIGA fabrication community is using the tool, where other efforts had failed. Another source of positive feedback is that the Microsystems design engineers (a separate group) has asked us to provide extensions to the Traveler to support their needs for tracing the development histories of parts they place in systems. Since these groups work together, we assume the fabrication group is reporting positively on our work.

An informal analysis, based on the number of hours our users reported spending on managing the old paper travelers suggests that the system may have saved the LIGA fabrication group at least $200K per year. Although informal, we feel this is a conservative figure. It does not include further timesavings resulting from the ability to access travelers at home and on travel, or in the role of our top-level screens in streamlining the Tuesday meetings.

Management of the fabrication group has indicated that the tool is contributing to their efforts to bring the LIGA process to the levels of maturity needed to move it into production. These efforts are bearing fruit: a recent design for a New Mexico application is achieving 100% yields. In addition, the managers of the LIGA group have invited us to present our work at a Microsystems conference this summer, indicating that they feel it is of interest, not just as software, but also as part of the broader LIGA effort. This is particularly positive, given our goal of becoming part of their community.

The most important feedback has come from our users. As mentioned earlier, the small size of the LIGA group allowed us to get to know the individuals involved. All of them have communicated their satisfaction with the tool. Perhaps what is most gratifying is that they do not hesitate to call us with questions or ideas for improvements. We take this as evidence that they do indeed experience us as situated in their community, goals and work.

## Acknowledgements

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