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Abstract

This paper describes the concurrent design of a wearable computer, called the Navigator. The design effort for the Navigator involved nineteen designers, representing a variety of engineering disciplines. The evolution of the design is described, with particular emphasis placed upon the role of the thermal design group in the overall design process. Furthermore, the particular challenges associated with the concurrent thermal management of wearable computer systems are outlined.

Introduction

Consumer desire for increased computational functionality has resulted in the development of portable computers. Portable computers, as exemplified by today's notebook machines, required technical innovations in both hardware and software to overcome the challenges presented by the associated size, weight, and power consumption constraints. Additional constraints, which arc market imposed, result from the highly competitive nature of the computer industry, necessitating shorter time-to-market, higher levels of quality, and reduced cost. The satisfaction of these competition driven constraints requires the achievement of domain specific objectives, such as clock speed, without the violation of any seemingly unrelated global constraints, such as reliability. Early resolution of constraints is essential since the time required for additional design iterations, necessitated to correct unanticipated flaws, is no longer available because product design cycles have been reduced to less than twelve months. Therefore, the participation of the entire design team is required to insure that a discipline-specific modification does not adversely affect other performance objectives.

The recognition of the multi-discipline nature of design has fostered interest in concurrent design, through which the concerns of a design team are accounted for in a collaborative fashion. This cooperative approach improves communication between designers, with the intent that resultant products are error free, and as such, correct-by-design. These products satisfy both the desire for high quality and shortened development cycles.

This paper will describe the concurrent design of a wearable computer, called the Navigator. The Navigator is the third generation of wearable computer products (Akella et al., 1992) developed at Carnegie Mellon University (CMU). The Navigator allows hands-off operation with a speaker-independent, 200 word vocabulary continuous speech recognition system for input and a see-through, heads-up display for output (Smailagic and Siewiorek, 1993). It provides wireless communication with a remote site. Position sensing provides the user's location so that information relevant to that location can be displayed. In some applications, such as manufacturing, we envision sensing the direction which the user is viewing, so that information specific to that viewing angle, such as an assembly step, can be displayed. Position sensing is currently used for the Navigator's application of self-guided navigation around the CMU campus. Likewise, different applications would require a variety of access rates to remote databases, resulting in a range of remote communication options from low data rate cellular phones over long distances to high bandwidth radio frequency local area networks.

The initial specifications for the Navigator included:

Functionality

- Dual mode of user input: speech and mouse
- Speaker independent, continuous speech recognition with 200 word vocabulary
- Capability to display text and graphics
- Miniature, light-weight, heads-up display
- On board database of information and maps
- Differential Global Position Sensing (GPS)
- Modem/wireless communication with remote site

Performance

- 80 - 90% accuracy in speech recognition
- Position sensing accurate to 5 meters
- Screen refresh should not distract the user
- Weigh less than 10 pounds
- Outdoor operating environment with rain, snow, and temperatures as low as -20° F
- Two-hour battery lifetime before recharging
- Cost less than $4500.00 per unit

A multi-disciplinary approach brings together personnel with vastly different expertise. The following disciplines are included in the design process:

- Electronics: electronic components, electronic interfacing, power supply
- Mechanical engineering: housing, thermal management, mechanical fixtures
- Software: operating systems and support software, such as user interface tools, libraries for position sensing and telecommunications, hardware drivers, etc.
- Human computer interaction (HO): speech and user interface

The design disciplines define the groups for the initial personnel organization. Subsequently, personnel are reassigned into interdisciplinary design teams as the various subsystems are identified and refined. The subsystems are the logical partitions of the whole system, initially along discipline boundaries, and the groups are the partitioning of the design team, where each group works on a subsystem.

During the spring of 1993 in the context of a design course, 19 designers (approximately split equally between undergraduate and graduate students), produced the Navigator wearable computer system, in less than 400 person days of effort Initially, the groups were composed as: Electronics 5, Mechanical Engineering 3, Software 6, and HCI 5 students. As the individual design stages are expanded, the dynamic utilization of personnel that resulted in a reallocation of the participants, is described.

Conceptual Design

For a multi-disciplinary, concurrent design process to be effective, it is important that team members cooperate, communicate, and share a common vision. Conceptual design is the setting for this beginning communication to take place, from which, a shared, common vision is developed. Without a common understanding or vision between the design groups and their members, each would be forced to rely on their own set of assumptions and criteria based only on a single view for the product.

The Navigator product concept is based on a modular design, in which each module performs a specific task. These tasks include visual display, speech recognition, position sensing, and telecommunications. Each task may have several implementations, allowing the system to be more flexible in order to meet the needs of a specific application. The Navigator problem definition requires a system that is capable of operating in a variety of configurations and applications.

From the perspective of flexibility, the modular concept offers many advantages for it enables the system to be adaptable to the needs of the user. The Navigator becomes a smart product where the user can individually tailor the unit according to application-specific needs. Additionally, modularity addresses the problem of repair and rework because defective modules can simply be unplugged and replaced.

During the conceptualization stage of the design evolution, the thermal designer participates by insuring that all team members are cognizant of cooling issues. By doing so, the design team can focus on concepts that satisfy their own objectives, while also minimizing heat production and accommodating any required cooling strategies. The requirement for outdoor usability virtually mandates the Navigator to be a closed, ventless system. Therefore, heat dissipation needs to be kept to as low a level as possible. Interestingly, the desire for extended battery life incorporates power minimization as a shared objective between the electronics and thermal designers. The envisioned modular approach is advantageous from the thermal perspective, for it subdivides the total power output and increases the surface area through which heat can be dissipated.

After the basic parameters are bound and an acceptable concept for the design specified, concurrent design is initiated. First, the concurrent design framework used by the Navigator design team will be outlined, stage by stage. A synopsis of the status of the other designers will be included for each stage. Following this, each design stage will be expanded from the perspective of **the** thermal designer. The specific issues and interactions related to the thermal designer are describecL . In this fashion, the role of the thermal designer in the concurrent development of the Navigator will be clearly depicted.

Concurrent Design Procedure

Throughout the design of the three generations of wearable computer systems, a Concurrent Engineering Methodology has evolved (Siewiorek et al., 1993). The goal of the methodology is to allow as much concurrency as possible during the design process. Concurrency is sought in both time and resources. The entire design cycle is divided into phases. Activities within a phase proceed in parallel, but are synchronized at phase boundaries. Furthermore, the tools used in concurrent design must be capable of handling increased complexity with the evolution of the product, thereby, satisfying both the accuracy and time constraints associated with a particular design stage (Nigen and Amon, 1992).

The design process is broken down into six sequential phases:

Technology survey

Alternative technologies are identified for each subsystem and evaluated in isolation from other subsystems. Alternative technologies are compared using a Model Feature Matrix based on information gathered mostly from product literature. A Model Feature Matrix is a concise summary of the technological alternatives arranged as a table, reflecting the attributes and characteristics that were identified as relevant during the project team and group meetings. The results of the Model Feature Matrices are used to identify primary and back-up alternatives for each of the subsystems.

System architecture specification

This phase attempts to integrate the results of the technology survey phase to produce the first concept of the total system. Interactions and interfaces between subsystems are identified and inconsistencies between subsystem alternatives are detected. Interactions between subsystems are summarized in a Design Dependency Matrix. A Design Dependency Matrix is an attribute dependency chart that identifies all dependencies on other projects and subgroups, and whether the dependencies have been resolved or are still open issues. These dependencies identify communication points for subsequent phases of the project. The primary technology alternative for each subsystem is refined to eliminate inconsistencies. Based on the refined set of technology alternatives, an architecture for the total system is specified.

Subsystem specification

Both firm and probable design decisions are identified and specifications are produced for each subsystem based on these design decisions. Interfaces to each subsystem are specified completely so that other subsystem designers can continue into the detailed design phase. Subsystem specifications are integrated into a complete Product Design Specification. A Product Design Specification defines three levels of specifications: subsystem, major system, and total system, with particular emphasis on interface behavior. This phase represents the last exploratory phase of the design process.

Detailed design

A detailed design of each subsystem is performed, with particular attention to maintaining the interface specifications as defined in the Product Design Specification. The technology selected for each subsystem is acquired and analyzed in terms of functionality and performance. Analysis of the technology may necessitate changes in the subsystem specifications. These changes are communicated to the relevant groups. Regular design reviews are held with group liaisons to ensure that interface specifications are not violated. Task Dependency Graphs are used to identify individual design decisions that affect more than one group, so that changes can be rapidly propagated. A Task Dependency Graph is a refinement of the Design Dependency Matrix and is used to explicitly identify interfaces between groups and identify potentially critical paths that might require additional resources.

Implementation

After detailed design is completed, each group implements its subsystem using the acquired technology. As implementation progresses, the subsystems are demonstrated at various stages of development A check list of open issues and action items is used to highlight remaining design dependencies and schedule their resolution.

System integration

Each subsystem is individually tested and then integrated into the final system. An Integration Tree is used to sequence the merging of subsystems along interfaces.

Next, the evolution of each design phase of the Navigator is presented and the perspective of the thermal designer is described.

Technology Survey

After reviewing the preexisting mobile systems, the project team brainstormed alternative goals for Navigator. Issues for evaluating design alternatives, such as cost, weight, and development time, were also identified A modular "mix-and-match" architecture incorporating speech input, position sensing, heads-up display, and telecommunications to a remote site was selected as the goal. A modular subsystem was formed for each goal. The target application was navigation around the CMU campus. In order to concurrently explore each of the technology alternatives, the project team was split into four generic subgroups: electronics, mechanical design/housing, system software, and applications. The technology survey phase was conducted independently by each group. Literature was surveyed, vendors contacted, and local experts consulted to identify potential options. The findings in the Technology Survey were reported as Model Feature Matrices, wherein, alternative models were listed and compared by the evaluation issues initially identified. Results of the Technology Survey phase were communicated to the project team during the group presentation that culminates the phase. Copies of the Technology Survey reports including product specification sheets were distributed to all team members.

From the thermal design perspective, the combination of portability and concurrency presents significant challenges. The premium placed upon power consumption, size, and weight discounts many of the previously popular cooling techniques. In the case of the Navigator, the situation is further complicated by the necessity of a ventless housing. As with many portable systems, a closed housing is desirable because the electronics are shielded from environmental contaminants and moisture. Cooling strategies for portable computers are further constrained by the desire to minimize parasitic power consumption, such as that required to drive a fan. Therefore, a more integrated approach is required, whereby, the housing is used as the heat sink and heat flow paths are carefully planned to insure adequate cooling for both reliability and comfort considerations.

The initial thermal design concept calls for the incorporation of "conductive fins" (Figure 1) that would directly connect heat producing components to the housing. The thermal performance of this approach suffers from the high contact resistances characteristic of solid-to-solid interfaces, which may become the limiting factor of the thermal performance, as well as temperature gradients between the package and housing surfaces. An alternative approach was described by Oktay (1993), which utilizes flexible heat pipes with variable cross-sectional area to connect heat producing components with the housing. Heat pipes offer the advantage of transferring high flux over long distances with minimal temperature drops, but retain the difficulties associated with contact resistances. Furthermore, flexible heat pipes are far more expensive and, as such, would only be incorporated if the conductive fin approach proved ineffective.

System Architecture Specification

The primary alternatives for each group were presented in detail to the other groups during team meetings. Subsystem interactions and dependencies were identified and used to indicate which design groups to notify if design decisions were made or modified. Compatible design alternatives were labeled resolved (i.e., the disk drive and the processor interfaced to the same bus, the operating system had a software device driver for the disk drive, etc.). Other dependencies were labeled unresolved and required future refinement in the next phase.

At this point, a new group was formed to focus on speech recognition since this appeared to be the subsystem which was the least well understood and developed. Sphinx 1 (Li et al., 1989) was selected as the primary alternative for speech recognition due to the availability of local experts. Mach (Rashid et al., 1989) was selected as the primary multi-tasking operating system, again due to local expertise. The Intel 80x86 processor family was the processor of choice for Mach. Since the 80386 had the highest performance and was the lowest power consuming 80x86 chip at the time of the project, design alternatives were narrowed to low power consuming boards based on the 80386. The only satisfactory alternative for display was found to be the Private Eye (Becker, 1992) and it became the default Other dependencies could not be resolved without further study. Both the resolved and unresolved design alternatives were discussed during the group presentations.

The thermal designer determined an approximate ratio between heat dissipation and required housing surface area through the use of Figures of Merit (Bar-Cohen, 1992), as shown in Figure 2. However, this lumped formulation required the assumption of a safety factor to account for the deviation between the average temperature of the system and the junction temperatures of the heat producing components. This can be especially significant in electronic systems because of the large degree of material variation and concentration of heat generation. The information provided by this analysis indicated the approximate number of housing modules required for the complete Navigator system. Additionally, through the use of simple one-dimensional analyses, proposed housing materials and thicknesses were evaluated relative to the thermal performance criterion.

The initial thermal design incorporated an integrated heat sink with conductive fins, which connect the heat producing components to the housing surface. Components along the outside perimeter of boards could be directly attached, but components within the central regions of the boards would require an alternate connection technique. The heat sink was composed of aluminum and was directly attached to the inside surface of the housing. An additional constraint associated with the heat sink was that no region of the housing outside surface should reach temperatures uncomfortable to the human touch.

Subsystem Specification

The goal of this phase is to produce an interface specification between subsystems so that the detailed design and implementation can proceed concurrently between groups. Subsystem specification represents the last exploratory phase of the design and combines both bottom-up and top-down features. For the top-down approach each major group provided a specification of their total system. For the bottom-up approach, each subgroup provided a specification for their subsystem with special emphasis on the interface behavior. The interfaces were specified in sufficient detail for other groups to continue into the next design phase. The subsystem specifications were combined into a Product Design Specification for the whole system.

After the hardware design team had selected the various components and boards, a solid model and elemental discretization were constructed in order to perform conduction simulations. Difficulty was encountered in the determination of material properties and power dissipation for each component As an example, the in-house designed board was expected, based upon manufacturer specifications, to dissipate 22.18 watts. However, experimental measurements indicated that only 7.50 watts were dissipated or 33.7% of the published values. Further complications result from the necessity of balancing computational viability with spatial resolution.

The Navigator is a multi-board, "real-world" system containing many components. To satisfy computational constraints, most of the components were represented by a single element, requiring modeling the packages as uniformly heat generating, single-material components. Krueger and Bar-Cohen (1992) have suggested a procedure whereby accurate thermal performance can still be obtained through the use of thermal influence coefficients. However, for this study, volume-weighted averages were used to model package material properties. Contact resistance was incorporated by placing a thin plane of elements between each package and its associated board. The conductivity of these "interface elements" was adjusted to match temperature drops commensurate with those found in actual systems (Yovanovich and Antonetti, 1988). The resulting mesh, displayed in Figure 3, consists of 660 macro-elements, each containing 125 degrees of freedom.

The first sequence of runs used constant surface temperature boundary conditions. Under these conditions, maximum temperature rise (AT) was obtained for the components. Although approximate, this information provides qualitative information as to the location of components which could exhibit high operating temperatures. It is essential for such information to be obtained early in the design process to allow for advantageous component placement relative to the attachment of conductive fins. Additionally, component placement can sometimes be rearranged to separate those that dissipate the largest amount of heat, but this must be accomplished without adversely affecting the computational performance of the artifact The housing design group also incorporated the available thermal-performance data, along with manufacturing and industrial criterion, to determine board and component orientations.

Component	Description	AT (°C)
ADM8038SX-25	processor	0.0036
ULSI 80386SX	coprocessor	0.0042
SIMS	Dynamic RAM	0.0338
+5 volt Power Supply	-	0.2116
-5 volt Power Supply	-	0.0485
Hard Drive	-	0.0023
LM350T	Voltage Regulator	0.0879
AOXVCGA	VGA	0.0084
LM7905	Voltage Regulator	0.1305
LM340	Voltage Regulator	0.1305

Table 1: Maximum temperature rise per component using constant surface temperature boundary conditions.

The results of these numerical simulations (Table 1) must be interpreted considering that the physically realized convective boundary conditions would be far lower than an infinite heat transfer coefficient. Seemingly small temperature increases above the prescribed surface values could correspond to significant temperature rises in the real system. Therefore, both the +5 and -5 volt power supplies on the custom board, as well as the LM7905 and LM340 on the A/D board, required direct attachment to the heat sink. Fortunately, all of these components are on the outside perimeter of their respective boards, which simplifies the design of the conductive fins.

Detailed Design

Once again, a subdivision and reassignment of personnel allowed for a focusing of resources on a maximally concurrent set of tasks. The subsystem interface behavior became the implied contract between the groups. Task Dependency Graphs were used to explicitly identify interfaces between groups and identify potential critical paths that required more resources.

The current implementation of the Sphinx 1 speech recognition algorithm does not run in real time, and hence, is unable to keep pace with a continuous stream of digitally converted speech input data. If a buffer is used to hold the input data, this implies that it will be filled at a faster rate than the data is consumed by the algorithm. To support an input buffer of finite size, a limit on the maximum duration of continuous speech input is necessary. Likewise, a mechanism is required for detecting the onset and discontinuation of speech and to enable and disable input stream buffering, respectively. Such a mechanism must run in real time and can be implemented in either hardware or software. Thus, a custom speech detection circuit was conceived and implemented as part of the Navigator design. This new board added to the power and housing requirements.

For this stage, the thermal designer conducted two types of numerical analyses. The first used the same mesh as used in the Subsystem Specification stage, except that the hottest components were attached to the heat sink. Special interface elements were placed between the top surface of these components and their associated conductive fins. In this fashion, the contact resistance was varied to determine the required amount of interface management to allow for satisfactory operating temperatures. This was especially important because interface management techniques can range from simple approaches, such as thermally conductive glues, greases, and pastes to relatively complex approaches, as exemplified by the use of springs and pistons in the IBM TCM (Chu and Simons, 1993). Therefore, through the variation of the conductive resistance within the interface elements, an adequate approach could be determined for each component For these simulations, satisfactory cooling was obtained with the interface element conductivities equal to ten times that of air.

An additional difference between the previous simulations lies in the imposition of convective boundary conditions rather than constant surface temperature. As always, determining the proper correlation for configurations that differ considerably from the idealized situation of flat plates with uniform heat flux or surface temperature is difficult A variety of correlations were used, ranging from parallel flat plates to those for natural convection in enclosures (Moffat and Ortega, 1988; Peterson and Ortega, 1990). For the later configuration, scaling analysis was used as indicated by Bejan (1984) to estimate the convective flow patterns from which, the proper correlation could be discerned. However, it was found that the predicted temperatures were not substantially different and, therefore, the most conservative values for the heat transfer coefficient were used. The results for the hottest components are displayed in Table 2 and graphically for the entire system in Figure

4 for an ambient temperature of 25* C. Both of these representations indicate that adequate cooling was achieved through the use of the integrated heat sink. Furthermore, the components that are the least sensitive to high operating temperatures, namely the voltage regulators and power supplies, exhibit the highest temperatures in the system.

Component	AT<°Q
ADM 8038SX-25	8.9861
ULSI 80386SX	5.8472
SIMS	10.3846
+5 volt Power Supply	23.3875
-5 volt Power Supply	14.9864
Hard Drive	9.0633
LM350T	14.2569
AOXVOGA	6.0659
LM7905	9.4834
LM340	10.4477

Table 2: Maximum temperature rise per component using a specified heat transfer coefficient as boundary conditions.

The second numerical analysis was carried out using a different mesh that incorporated the air gaps between the boards and housing, as well as the housing material. This mesh was also used in the following stage to conduct a conjugate conduction/convection simulation. However, for this stage, only a conduction simulation was performed. Owing to the large computational requirements associated with a conjugate study of the Navigator, the construction of an approximate mesh was required, wherein, each board/component level was modeled as a plane. The regions of each plane corresponding to the location of heat producing components are specified to uniformly generate heat. The purpose of this simulation was to determine the surface temperatures of the housing and to further check the basic indications provided by the preceding simulations. Furthermore, the very close proximity (less than 0.5 cm) of many of the boards, coupled with the surface height variation caused by the components, would serve to reduce convective velocities and as such, this analysis served as a worse case estimate. The temperature field, shown in Figure 5, indicates that acceptable operating temperatures arc obtained, and that the exterior of the housing exhibits satisfactory temperatures from a comfort perspective.

Implementation

As each group implements their subsystem, an evolving list of open issues, action items, and responsible designers to perform them is used to indicate the remaining design dependencies and how they will be resolved. A progression of logical milestones is monitored, including demonstrations and written reports.

In this phase, the development of a speech subsystem was completed and the code ported to the open-air system. A microphone and Analog to Digital Converter (A/D) were added to the open-air system. Software drivers, supplied with the A/D board, were used to write the microphone samples to a RAM disk. An interrupt from an audio level detector triggers data collection and a serial line driver was used to send data between DOS and Mach computers.

The thermal designer carried out a conjugate conduction/convection simulation during this stage. As this is the last stage before system integration, it is essential that any possible thermal problems be determined. The previous simulations indicated that the heat sink/conductive fin combination proved adequate in maintaining acceptable operating temperatures. Therefore, the thermal designer related this information to the entire product development team.

The Navigator electronics were composed of mostly off-shelf components and would require mounting fixtures within the housing. However, the housing was manufactured using pressure forming which disallows integration of mounting fixtures. Furthermore, the operating environment for the Navigator necessitates rigidity for integrity. Therefore, the heat sink was modified such that it incorporated fixtures for the boards and components, as well as increased the rigidity of the housing. This design effort required a collaborative effort between all of the participants of the housing design group.

System Integration

The final design phase was to bring all the subsystems together, exercising their interfaces. An Integration Tree was used to sequence the integration steps and set deadlines for the next step.

Speech was integrated with the campus application software. An object model was defined for the navigation task which included the capability to provide information concerning an individual, as well as provide a route to their campus location.

During this stage, the Navigator was experimentally tested by the thermal designer. As with all numerical investigations/designs, experimental verification is required to insure the accuracy of the modeling procedure. Thermocouples were used to measure the operating temperatures of the components. It should be noted that qualitative measurements indicate that the operating temperatures were within the predicted range and are not excessive. Furthermore, the +5 volt power source was the hottest component within the system.

As the system was assembled, corrections were made to the conductive fins to conform to attachment specifications. Additional modifications were required to accommodate pins that penetrated through adjacent boards. However, it should be emphasized that no additional effort was needed to correct errors associated with miscommunications during the Navigator design.

The completed Navigator is shown in Figure 6 and Figure 7. Figure 6 displays the navigator electronics and subsystems prior to assembly, while Figure 7 shows the complete system, including the housing and belts.

Summary

Navigator's designers were dynamically reallocated four times during the design process as new tasks were identified. Two development platforms were utilized. A PC platform allowed initial software development. A bench-top, open-air configuration of the final hardware components augmented by Ethernet interface, console monitor, and keyboard allowed software integration prior to availability of the final packaged wearable system. An extensive array of communications techniques were used including group presentations, progress reviews, group meetings, and group liaisons. The communications techniques and resources were dynamically modified throughout a six stage design process described earlier.

Personnel

Initially, the Navigator was decomposed into subsystems corresponding to the various disciplines involved, i.e., electronics, mechanical engineering, systems software, and human computer interface (HCI). Additional subsystems were formed to allow more concurrency in the total design process and improve organization by focusing group efforts. As the design process progressed, the resource requirements of each group changed. Designers were reallocated from one group to another to meet new resource demands in the form of additional people power and expertise.

In the detailed design phase, the scope of each group was better understood. The ability to reallocate personnel allowed for these new needs to be met For example, the applications group initially believed that their two person team would be sufficient, since the concept for the application of a campus tour seemed reasonable from the programming perspective. As the design of the campus navigation system was developed, it was clear that there were many aspects of the application that needed to be addressed. There were interface issues with speech and GPS along with the design of the user interface. Thus, it was realized that two designers were insufficient to complete the design on time and it was necessary to reallocate three people from the systems software group to help with the applications development. Figure 8 depicts the evolution of personnel assignments where the numbers indicate the people involved.

In parallel with the development of the various electronics and software subsystems, mock prototypes of the final system housing were built by the mechanics group to model ergonomics. As the open-air system developed, however, problems were revealed that needed to be considered by the mechanical group, e.g., constraints on buses interconnecting the various modules. Also, electrical interference and heat dissipation experiments were performed to study interactions among the electronic components of the open-air system. Therefore, the prototypes were continuously refined and updated as the open-air system evolved.

Communications

Communications were in the form of design proposals, survey summaries, and demonstrations. Group presentations allowed communication and exchanging of ideas and exposed results of a phase.

The communication patterns between groups varied with the design phases and certain forms of communication were better suited to particular phases. The goal of the technology survey is to identify and evaluate alternative technologies for each subsystem. Since alternative technologies were surveyed independently for each subsystem, little communication was needed between design groups. Thus in this phase, the main form of communication was presentations that shared survey results. In the system specification stage, the first concepts for the total system were explored Therefore, it was very important for ideas to be exchanged on what the composition would be for each subsystem. Each group had brainstorming meetings to produce ideas for their subsystems. The results of these meetings were shared in group presentations, leading to discussions on issues related to interactions and interfaces between subsystems.

As the design moved into the Subsystem Specification and Detailed Design phases, there was an increased need for inter-group communications, since these stages involved design of interfaces between subsystems. To facilitate communications between the groups, liaisons were appointed, who participated in group meetings of several groups. The function of the liaisons was to detect interface and interaction problems between groups, as well as to help identify hidden problems within the groups. During these phases, electronic mail became an increasingly used medium for discussing interface questions between groups.

In the implementation phase, each subsystem was built according to the detailed design done in the previous phase. Within each group, individuals were assigned by the group to different tasks. Thus, less time was spent in group meetings as people worked on their assigned tasks. E-mail traffic increased as individuals would encounter problems which affected many people within and outside their groups. During this phase, there were e-mail announcements of incremental progress as people completed subtasks.

In the implementation and integration phases, communication was mainly in the form of progress reviews to update the status of each group, to set new milestones, and to allow problems to be communicated between groups. As subsystem implementation progressed, interaction between groups increased because changes in one group affected the implementation of another group's subsystem.

The integration phase required more communication between all project members. In this phase, the subsystems were assembled into a total system. Problems were encountered as the subsystems were merged together, requiring the attention of the affected groups. Thus, communication among all the project members was very important. Progress reviews addressed these integration problems, so that groups could see if they were affected.

Effort

The relationship between discipline personhours and phases is shown in Table 3. The four rows correspond to the disciplines involved in the project: Electronics, Mechanical Engineering, Human-computer interaction, and Software. The six phases of the project are represented in the corresponding columns. It was concluded that the final design is well balanced: most of the time was spent in the detailed design (38%) and implementation (24%) phases, and the other four phases consumed almost an equal percentage of time (8-11%). Should an inadequate effort been made in the recognition of design team inter-dependencies, a significantly larger amount of time would have been required in the integration phase to correct problems.

Conclusions

This paper outlines the concurrent thermal design of a wearable computer called the Navigator. The generic Concurrent Design Procedure is presented and the role of the thermal designer in each design stage is described. A variety of thermal analysis techniques were used, ranging from approximate Figures of Merit and one-dimensional models, to scaling analysis, and finally to direct numerical simulations with conjugate conduction/convection formulation. Each of these approaches was carefully selected to provide required information to other designers, as well as to balance time constraints associated with a specific design phase. Contributions made by the thermal design group, ranged from evaluation of heat dissipation limitations of each subsystem module to providing operating temperatures of the various components.

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Figure Captions

\£hases \ Disciplines.	Technology Survey	System Architect.	Subsystem Spec.	Detailed Design	Implement-ation	System Integration	Total
EL	98	80	130	440	209	112	1069
ME	48	49	57	185	140	50	529
HCI	64	64	80	315	205	73	801
SW	70	56	75	242	191	76	710
Total	280	249	342	1182	745	311	3109

Table 3 Discipline personhours per Phase

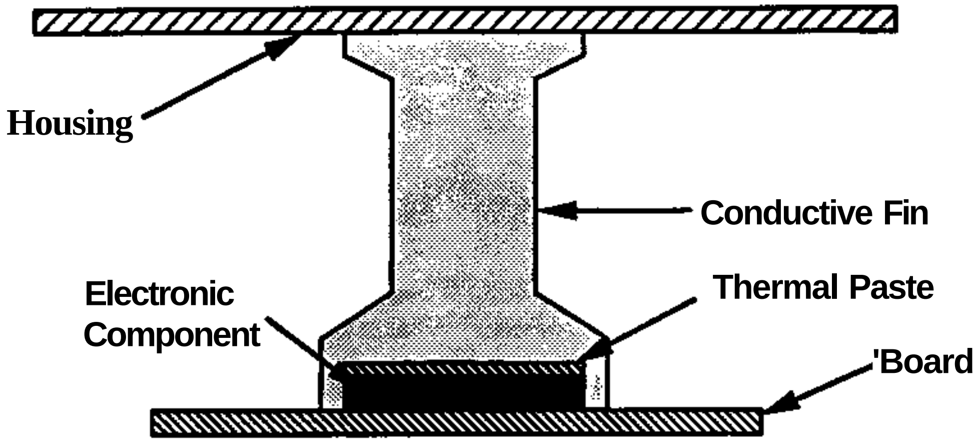

Housing
Conductive Fin
Electronic
Component
Thermal Paste
'Board

Fig. 1

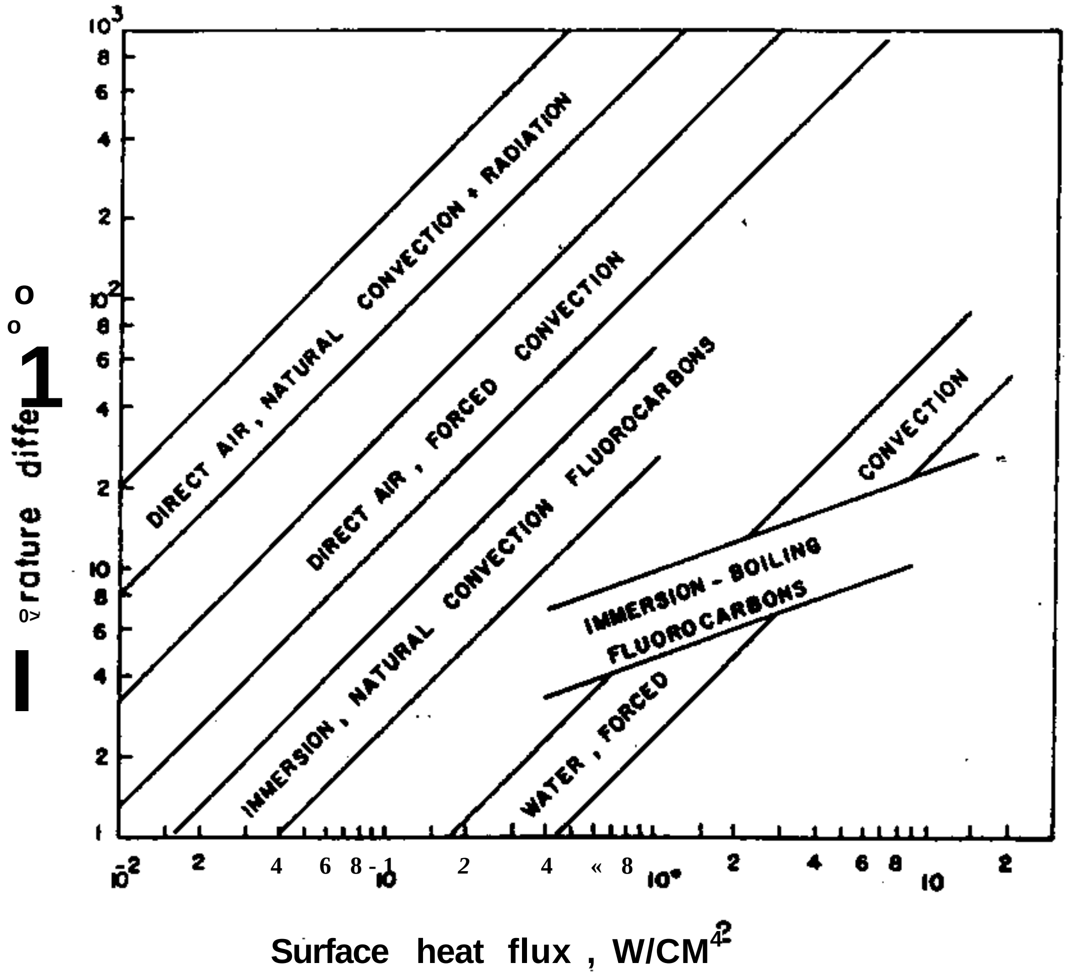

DIRECT AIR, NATURAL CONVECTION + RADIATION
DIRECT AIR, FORCED CONVECTION
IMMERSION, NATURAL CONVECTION FLUOROCARBONS
IMMERSION - BOILING FLUOROCARBONS
CONVECTION
WATER, FORCED
Surface heat flux, W/CM2

Fig. 2

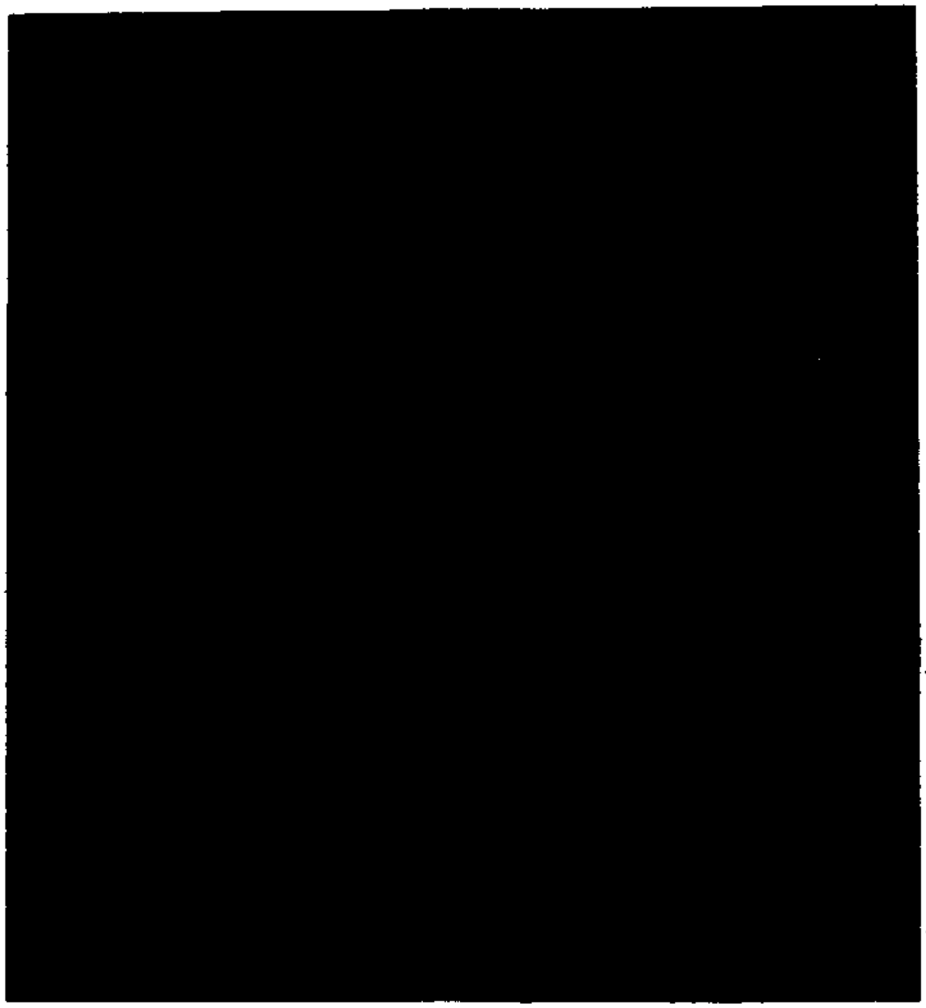


Fig. 3

Smailagic et al.

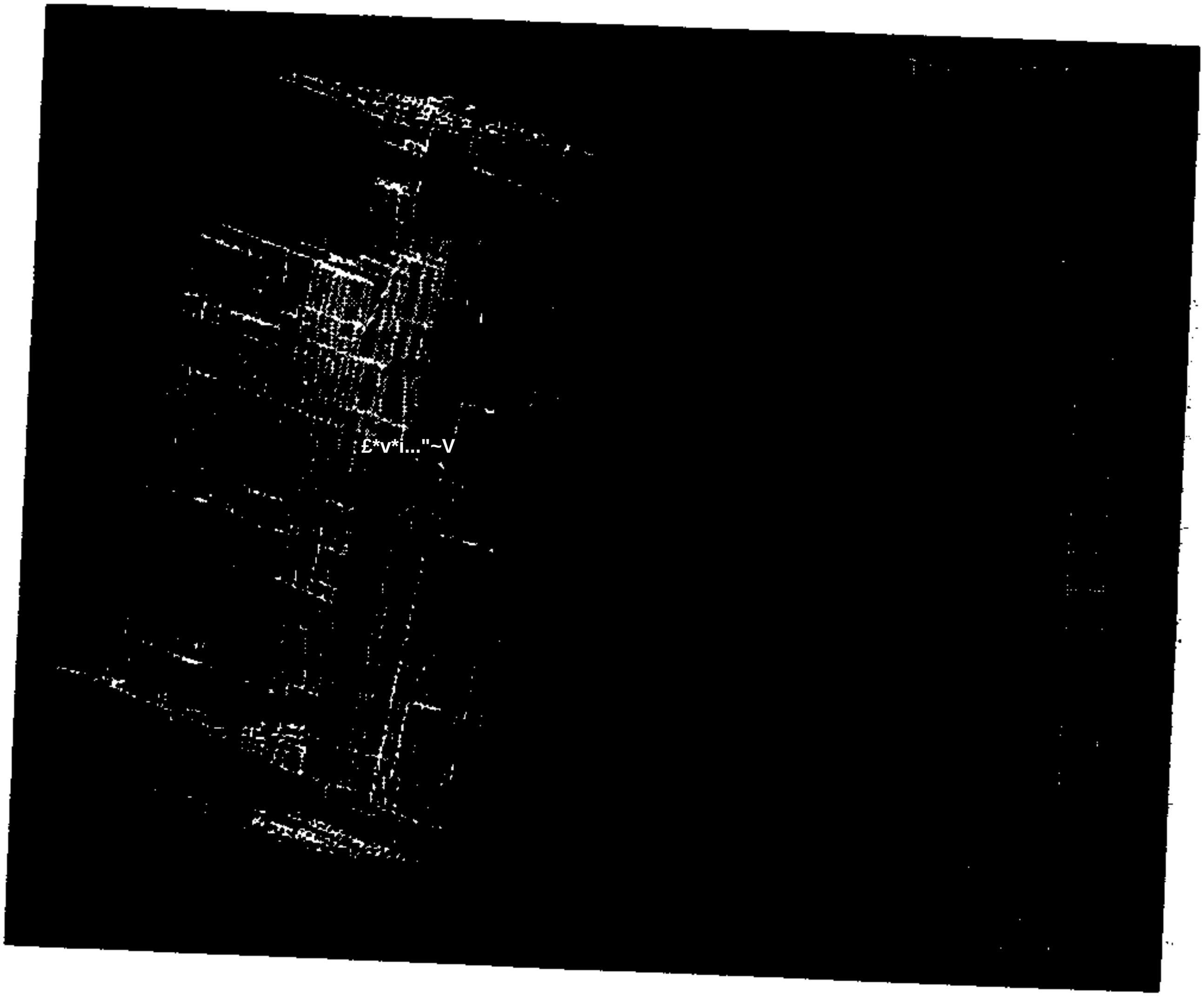


Fig. 4

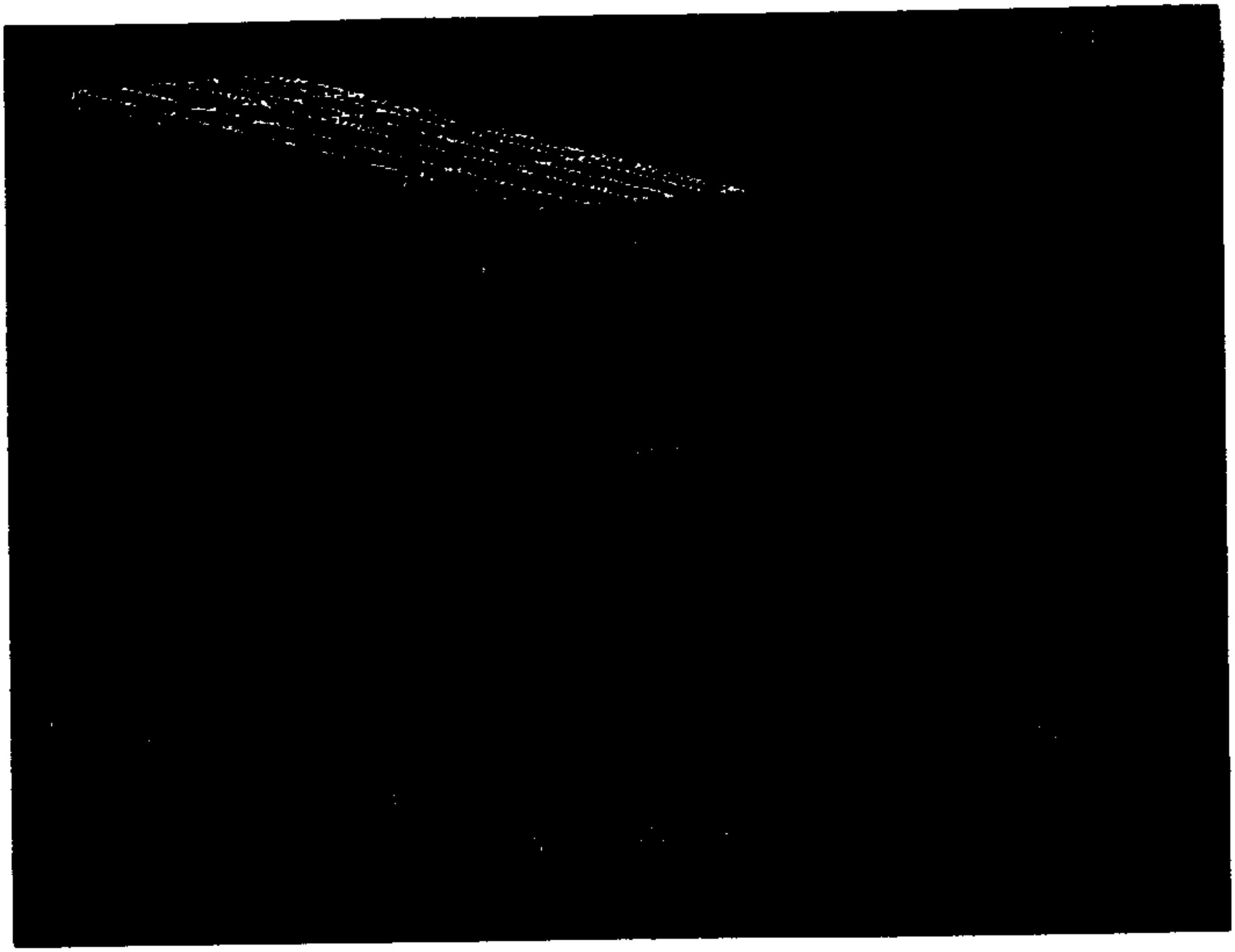


Fig. 5

Smailagic et al.

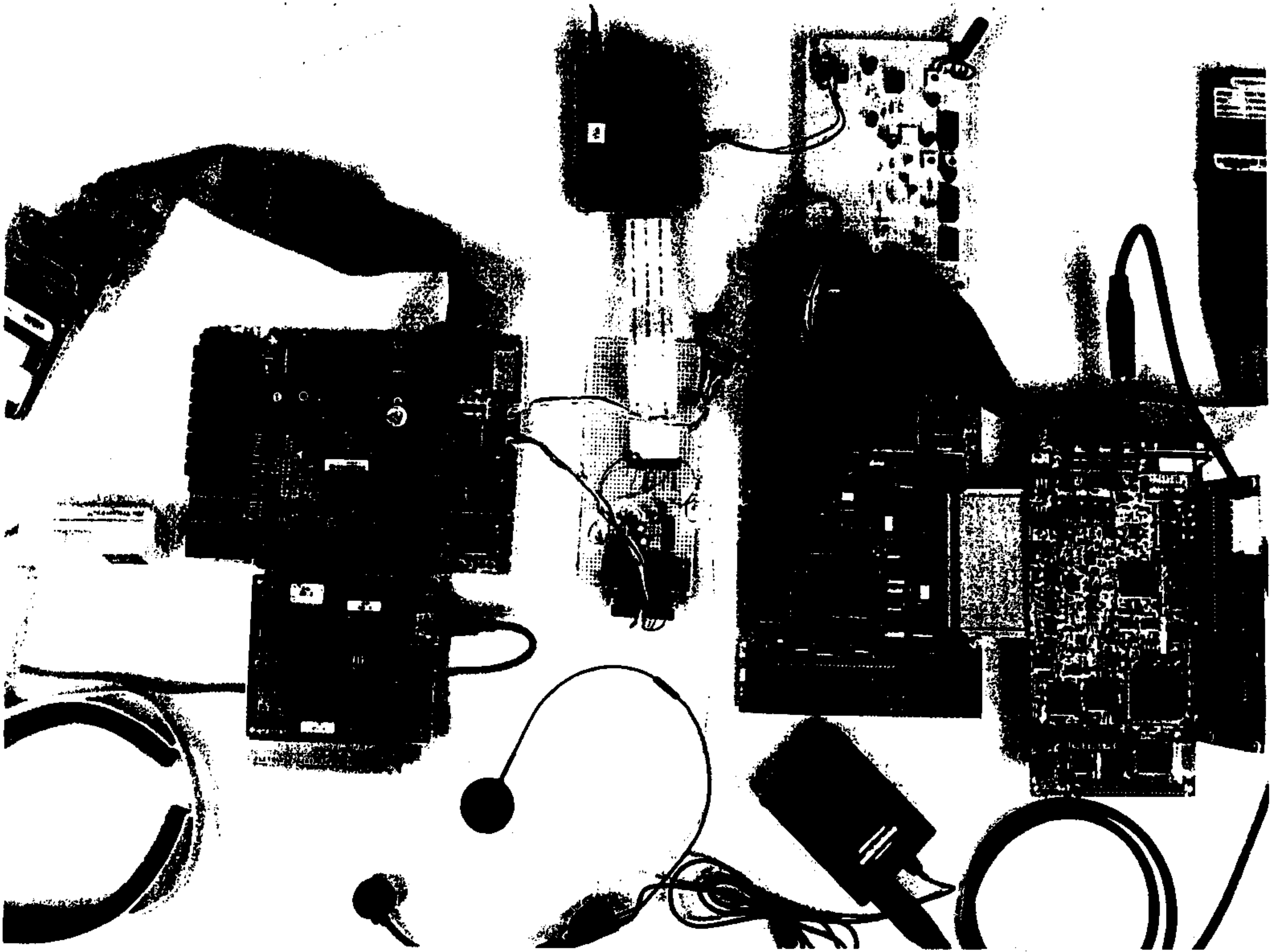


Fig. 6

Smailagic et al.

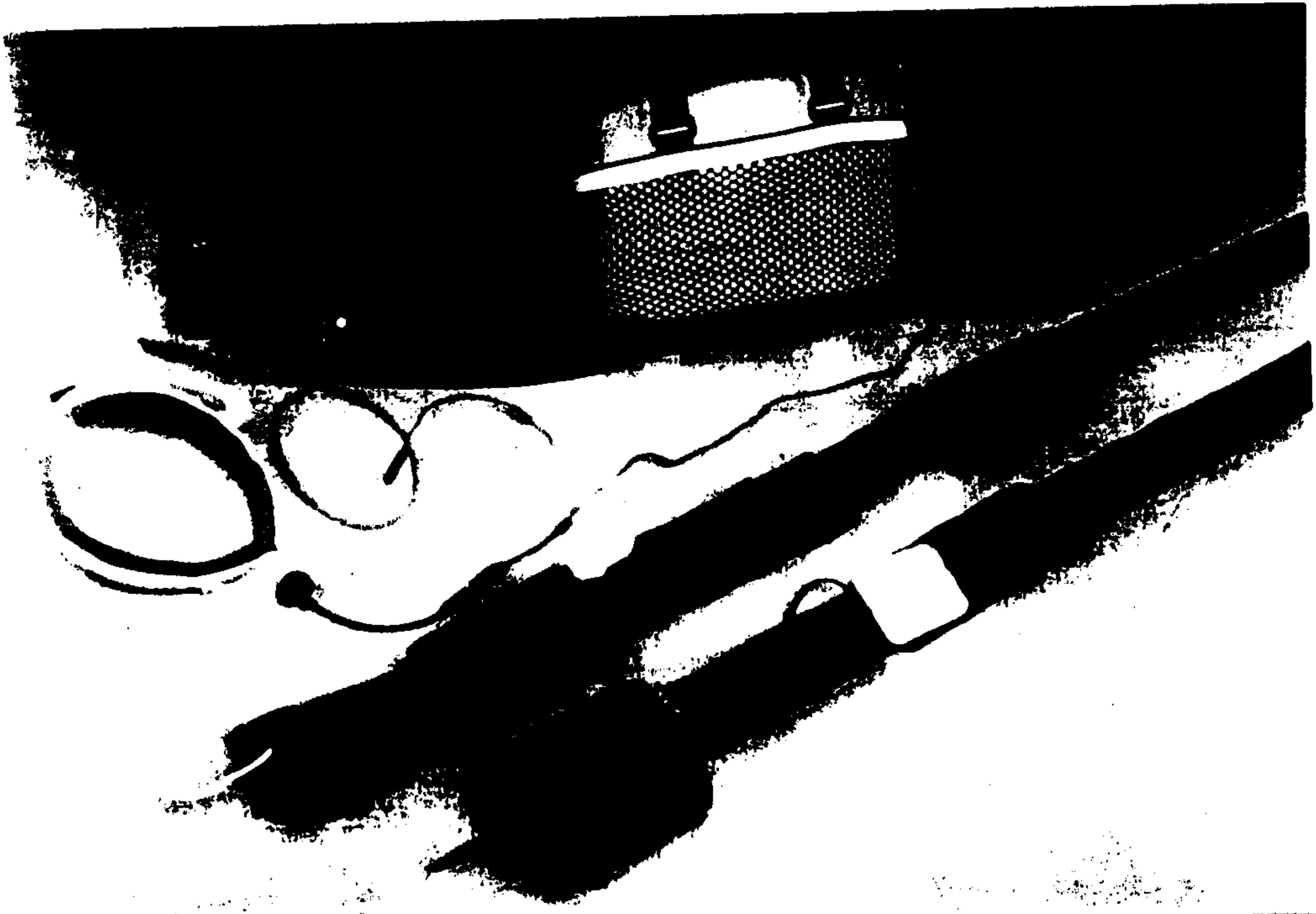
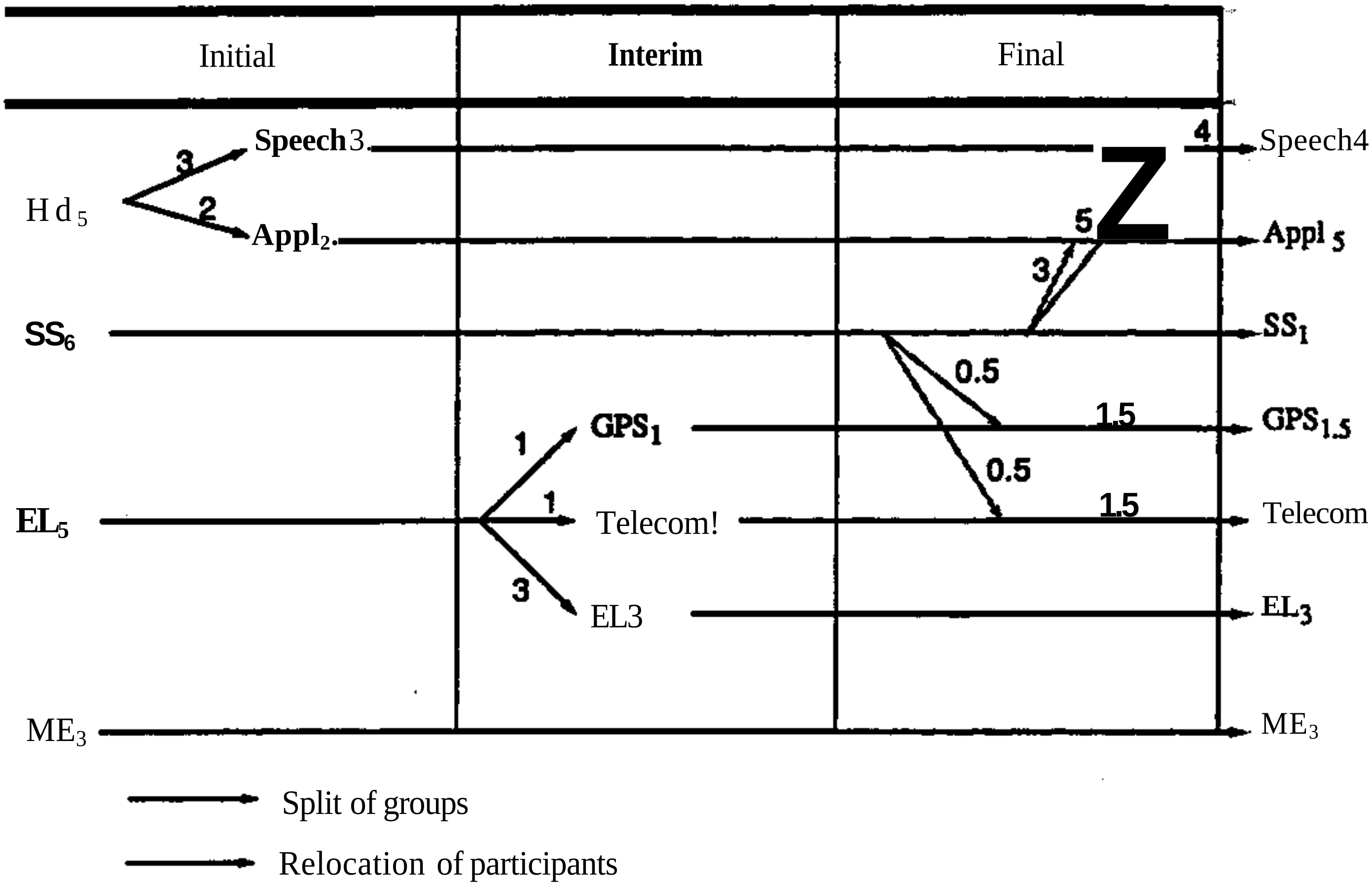


Fig 7



Initial
Interim
Final
Speech3
Speech4
Hd5
Appl2
Appl 5
SS6
SS1
GPS1
GPS1.5
EL5
Telecom!
Telecom
EL3
EL3
ME3
ME3
3
2
4
5
3
0.5
1.5
0.5
1.5
1
1
3
Split of groups
Relocation of participants

Fig. 8