(3) CW/ IN/ 60

USING WEARABLE COMPUTERS IN SHUTTLE PROCESSING: A FEASIBILITY STUDY[1]

Martha A. Centeno
Industrial and Systems Engineering
Florida International University
Miami, Fl 33199

Daisy Correa
Marcia Groh-Hammond
Shuttle Process Integration - PH-M1-B
Kennedy Space Center, Fl 32899

1. INTRODUCTION

Shuttle processing operations are performed following prescribed instructions compiled in a Work Authorization Document (WAD). Until very recently, WADs were printed so that they could be properly executed, including the buy off of each and every step by the appropriate authorizing agent. However, with the development of EPICs, Maximo, and PeopleSoft applications, some of these documents are now available in electronic format; hence, it is possible for technicians and engineers to access them on line and buy off the steps electronically. To take full advantage of these developments, technicians need access to such documents at the point of job execution. Body wearable computers present an opportunity to develop a WAD delivery system that enables access while preserving technician's mobility, safety levels, and quality of work done.

The primary objectives of this project were to determine if body wearable computers are a feasible delivery system for WADs. More specifically, identify and recommend specific brands of body wearable computers readily available on the market. Thus, this effort has field-tested this technology in two areas of shuttle processing, and it has examined the usability of the technology. Results of two field tests and a Human Factors Usability Test are presented. Section 2 provides a description of the body wearable computer technology. Section 3 presents the test at the Space Shuttle Main Engine (SSME) Shop. Section 4 presents the results of the integration test at the Solid Rocket Boosters Assembly and Refurbishing Facility (SRBARF). Section 5 presents the results of the usability test done at the Operations Support Building (OSB).

2. WEARABLE COMPUTERS TECHNOLOGY

Wearable computers are small size PC's that differ from Pocket PCs at the hardware as well as the operating system level. Wearable computers are just like any desktop PC or Laptop. As such, they use the same operating system as a PC, whether it is Windows, Windows NT, or Linux. Hence, they can run any application that a regular PC can run. Wearable computers may have the elements described in Table 1. Exactly which combination of elements is required depends on the type of job to be done and the software to be used for it.

The processor for wearable computers will continue to evolve paralleling that of processors for regular PCs. At present, the chip and motherboard size are a lot smaller than the one used in regular PC; hence, the technology is moving about one step behind that of a regular PC. This means that available speeds on a wearable unit will be slower than that of current PCs or laptops. In regards to display devices, wearable units normally come with a flat panel with a built-in touch screen, but they can also be fitted a Heads Up Display Device (HUD). The flat panel size is as big as 9 inches. Larger panel are possible but are unlikely to appear on the market, as they would defeat the goal of the unit being wearable. Smaller panels are also possible; however, the functionality of it on the workplace may be diminished. Smaller panels may be functional for text-based output only. If the output is graphics-based, however, a large screen may be required to avoid continuous scrolling of the screen to see the information needed.

An alternative to the flat panel is the heads up display (HUD) device (Figure 1). Typically, the manufacturer of the wearable unit is not the manufacturer of the HUD. They simply partner with someone who produces the HUD and fit it to their unit. There are two basic types of HUDs: 1) binocular and 2) monocular. Binocular HUDs are good for training and virtual reality work. The user receives all the information via the HUD, and he or she is not

---

[1] This effort was funded under NASA grant NAG10-292 and a NASA/A.S.E.E. Fellowship.

required to move around. Monocular HUDs come either as "see-through" or "see-around" displays. This type of HUD is good when the user has to move around, and he or she is required to read additional information outside the HUD. Current HUDs are either color or monochrome displays. The resolution of the display is restricted to a maximum of a 640x800 resolution. The technology is also advancing to allow for depth of display adjustment, so that it can simulate projection at 2, 4, or 8 feet. Some prototype models of HUDs allow for the display element to be moved away from the plane of sight as needed.

CPU	o Pentium Based Chip. o Chip speeds of 233 MHz and up; latest model are running 800 MHz. o Hard disk of 6 GB and up. Some of the smallest model may have smaller drives of only 3 GB. o RAM memory of 64 MB and up. The current limit is 512 MB. o USB port. o Customized port to plug in a port replicator. Out of the port replicator it is possible to have serial ports, mouse and keyboard ports, and video ports. o Some of the CPUs have an integrated mouse.
DATA DISPLAY	o Flat Panel (6 or 9 inches of viewable screen). o Heads up display. Depending on the manufacturer, the HUD could be a monocular, see through or see around display; or it could be a binocular semi or full immersion HUD.
DATA ENTRY	o Flat Panel Touch screen. o Mini keyboard. o External handheld mouse. o Head set with microphone.
NETWORKING	o PCMCIA cards for hardwire connectivity as well as for wireless connectivity.
OTHER ACCESSORIES	o PCMCIA based CD drive. o Mini keyboard through additional ports. o Docking station, with multiple ports for floppy diskettes and similar devices.

Table 1: Elements of a Wearable Computer

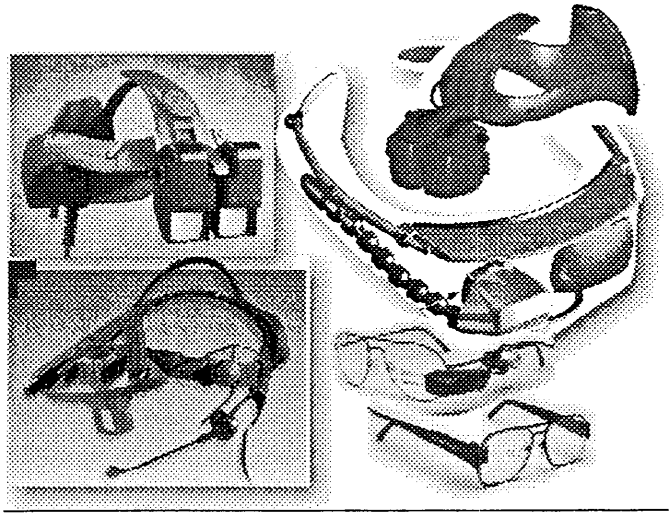


Figure 1: Some HUDs

When fitted with a HUD, the user has the option of a mini keyboard or voice command for data entry. Screen navigation can be done via voice command or via mouse. Voice command requires the acquisition of a voice recognition program, such as ViaVoice from IBM. The technology for voice recognition has made significant progress, but it is still a bit difficult to use, as it requires individual voice recognition training. Furthermore, it does not work well when the work environment is a bit noisy, even in low-level noise. Nonetheless, significant progress is expected in the next few years.

In regards to networking capabilities, a wearable computer has the same capabilities as a regular PC. The units require the use of a PCMCIA type of card to connect to a network in either a wired or wireless form. Using a wearable computer in a wired or wireless network is totally dependent on how the user is supposed to be working. There is one concern in regards to the use of this technology in a wireless environment, and that is that the card communicates with the wireless network via RF signals. In environments where explosive are handled, this option may not be advisable. The lack of wireless connectivity does not prohibit the use of the wearable computers technology as the information regarding WADs could be preloaded, and the data entered by the user could then be uploaded to the network via a wired connection.

Commercially, there are three main players: Xybernaut, VIA, and Perkins Engineering. Xybernaut is the leader on the market. They have been manufacturing wearable computers for several years. Figure 2 shows their Mobile Assistant IV (MA IV) model. Their latest model, the Mobile Assistant V (MA V) is the product of a partnership with IBM. The MA V was released to the market during the summer 2001. Figure 3 shows the unit from Via. It is very light and seats on a regular belt. The CPU wraps around the back of the user. Figure 4 shows the Perkins Engineering's unit called Mid-Riff Brain (MRB). The unit is just as robust as the MA IV. One advantage of the MRB is the belt upon which the unit is carried. The MRB's belt is fully adjustable and very light, and it has an articulating arm that holds the flat panel display.

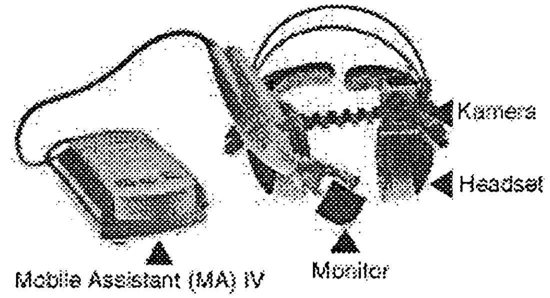


Figure 2: Xybernaut's Wearable Unit

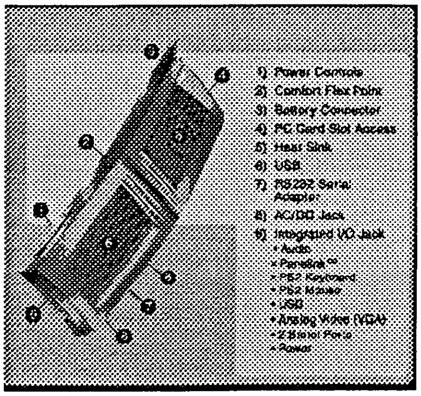


Figure 3: VIA Wearable Unit

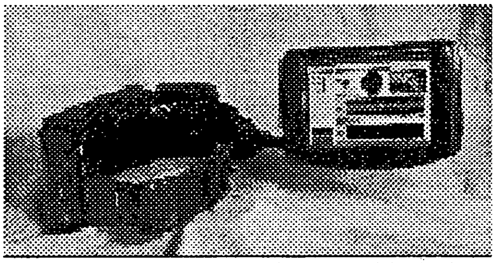


Figure 4: Mid Riff Brain Wearable Unit

3. WEARABLE COMPUTERS FOR SSME RECEIVING INSPECTION

The primary goal of this test was to establish the benefits of using a wearable computer to process the WAD V6033 N: SSME Receiving Inspection. The test was done in the SSME shop, located in the OPF 3 Annex. This was a first trial on field-testing the MA IV as well as on the test procedure itself. Technicians were given little or no training. The number of technicians that participated in the test was five. The test required the use of a laptop, wearable unit, and paper based to engage in parallel processing of the WAD for comparison purposes. The real buying was done on the paper version. Rocketdyne developed the software used for the electronic buys. Acceptance by the user was measured via direct observations and post-trial questionnaires addressing two distinct processes: 1) *Assembling the unit*, and 2) *Interaction with the Unit*. For the interaction with the unit, four aspects were studied: Physical, Mobility, Data Entry, and Data Display.

Only three of the five technicians that were somehow involved in the test actually used the wearable computer. From an overall point of view, there was great variation in their responses (Table 2). 10.53% found at least one aspect of the unit highly difficult to interact with. A large 38.60% were dubious about how easy it is to work with this unit. Only 50.8% thought it was relatively easy to work with the unit. A closer look to the responses to each aspect reveals that it seems that the overall weight of the wearable computer is OK. The only instance in which there may be a problem is in the continuous use of the touch screen on the arm; after awhile, the weight of the touch screen becomes too much. Furthermore, constant use of the touch screen on the arm limits technicians' ability to reach where they need to reach. A percentage-based analysis reveals that the *data display aspect* received a very low ranking, getting no positive ranking whatsoever, and an 80% of ambivalent Reponses. On the other hand, the *data entry aspect* received 75% high rankings, and it only got 12.5% negative responses. For the other aspects, the ambivalent posture was significant, but the negative rating was low. Thus, the display was the one that disenchanted the technicians.

In general, technicians seem to like the idea of using a wearable computer to do their job, but not necessarily in the SSME shop and not necessarily for this WAD. Their main concern seems to be the effect of any radiated energy. This needs to be addressed. Use of the wireless network is the main source of radiation.

	Negative	**Ambivalent**	**Positive**
Overall	10.53%	38.60%	50.88%
Display	20.00%	80.00%	- -
Data Entry	12.50%	12.50%	75.00%
Mobility	8.33%	50.00%	41.67%
Physical	8.33%	41.67	50.00%

Table 2: Frequency of Responses – Interaction

4. WEARABLE COMPUTER USAGE FOR TPS AUTOMATED THICKNESS MEASUREMENT

The primary goal of this test was to establish the benefits of using a wearable computer as part of an integrated system that fully automates the TPS Thickness Measurement Activity. Full scale integration of wearable computers required a two-phase approach: 1) evaluate and test the integration of the hardware and 2) test the integrated system with the help of the technicians. The current system (Figure 5) has been performing well; however, it has gotten obsolete, and it fails to take advantage of current data analysis packages. Under the current system, technicians write the value read from the KUDA sensor on a paper map of the corresponding SRB structure (Figure 6). Since the data resides on paper, it only gets analyze on a reactive mode. Hence, it needs to be replaced with a system that allows on-line data collection and proactive data analysis. Figure 7 shows a conceptual proposed system using the wearable unit from Xybernaut (MA IV). Our test proved that such integration is feasible.

The new KUDA sensor was tested for accuracy and for compatibility with a wearable unit. To achieve this, a software application was developed by a USA SRBARF team, using RSView32. The hypotheses being tested are given in Table 3. The tests of hypothesis revealed that there is no statistical difference in readings between the sensors when doing it under calibration. However, Table 4 shows that there may be a minor hidden difference on the reading of 1 unit (mean value = -1). It appears that the new sensor is consistently reading one unit higher than the current sensor (85% of the time). This is visible from the position of the confidence interval on the horizontal axis. The good thing is that such variation is consistent across all readings as they have a perfect positive correlation ($\rho = 1$, Figure 8).

The tests of hypothesis for actual readings revealed that ***there is*** a statistical difference in readings between the sensors (Table 4). However, this table also shows that once again, it appears that the new sensor is consistently reading 2 units higher than the current sensor (mean value = -2.04), and that the confidence interval's upper limit is very close to 0. Once again, the good thing is that such variation is consistent across all readings as they have a strong positive correlation ($\rho = .982$, Figure 9). Hence, although the test says that there is a statistically significant difference, we know that the difference is on the new sensor giving higher readings by 2 units on the average. This can be removed by recalibrating the sensor, i.e. by offsetting its zero point. This can be done with 95% confidence and with the assurance that indeed the two sensors are paralleling their behavior as shown in Figure 10 and Figure 11.

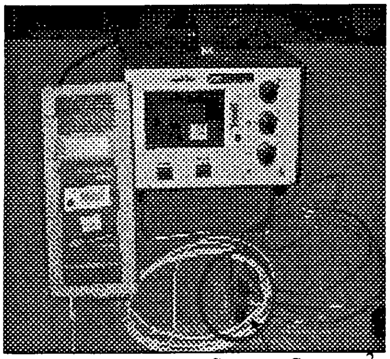


Figure 5: Current Sensor System[2]

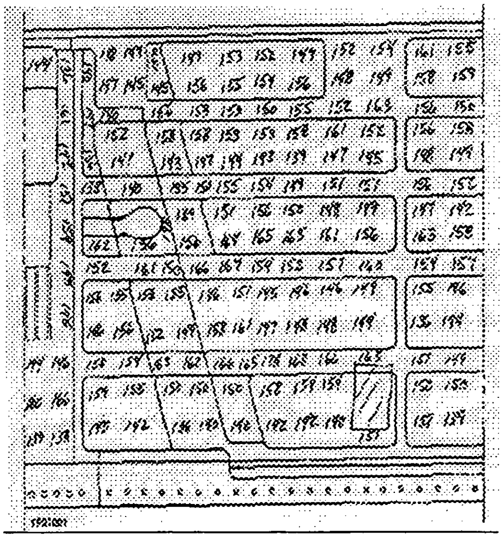
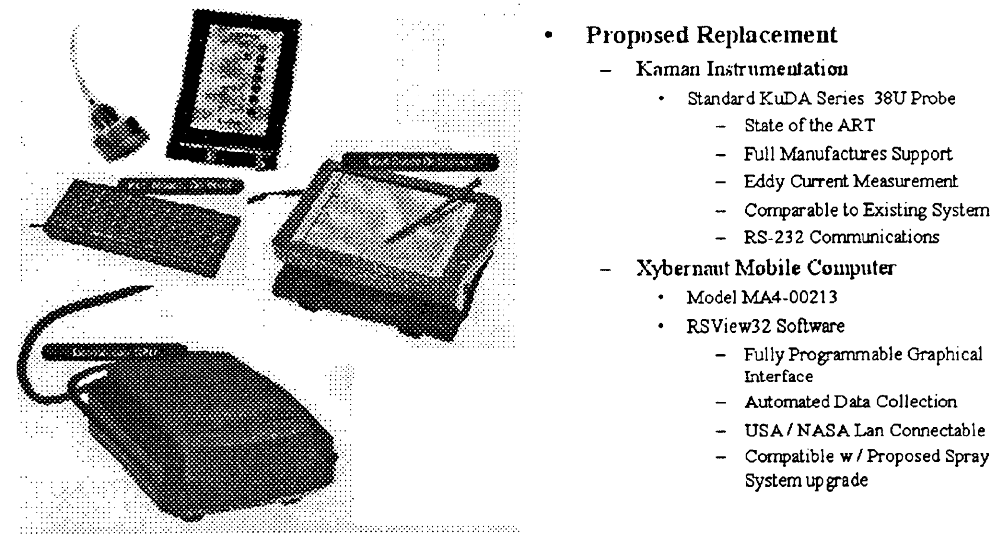


Figure 6: Sample Map of Data Points – Paper-Based



- **Proposed Replacement**
  - Kaman Instrumentation
    - Standard KuDA Series 38U Probe
      - State of the ART
      - Full Manufactures Support
      - Eddy Current Measurement
      - Comparable to Existing System
      - RS-232 Communications
  - Xybernaut Mobile Computer
    - Model MA4-00213
    - RSView32 Software
      - Fully Programmable Graphical Interface
      - Automated Data Collection
      - USA / NASA Lan Connectable
      - Compatible w / Proposed Spray System upgrade

Figure 7: New KUDA System – Proposed

Hypothesis 1:	**Hypothesis 2:**
$H_0 : \mu_{cc} = \mu_{nc}$ Converted to → $H_0 : \delta_1 = 0$ $H_1 : \mu_{cc} \neq \mu_{nc}$ $H_1 : \delta_1 \neq 0$	$H_0 : \mu_{ca} = \mu_{na}$ Converted to → $H_0 : \delta_2 = 0$ $H_1 : \mu_{ca} \neq \mu_{na}$ $H_1 : \delta_2 \neq 0$
δ_1 = Difference between population means (current – new)	δ_2 = Difference between population means (current – new)
μ_{cc} = Average readings with the current sensor - calibration.	μ_{ca} = Average readings with the current sensor – actual.
μ_{nc} = Average readings with the new sensor - calibration.	μ_{na} = Average readings with the new sensor - actual.

---

[2] Figure 5 to Figure 7 were taken from a PowerPoint Presentation developed by USA SRBARF personnel

Table 3: Hypotheses tested – SRBARF

	MEAN	STD. DEVIATION	STD. ERROR MEAN	CI LOWER	CI UPPER
CURRCALI - NEWCALI	-1.0000	1.5275	.5774	-2.4127	.4127
CURRCALI	299.143	216.4882	81.8249	**CORRELATION**	ρ
NEWCALI	300.143	215.9517	81.6221	CurrCali & NewCali	1.00
CURRENT - NEWKUDA	-2.0476	1.7169	.3747	-2.8291	-1.2661
CURRENT	190.9048	8.9661	1.9566	**CORRELATION**	ρ
NEWKUDA	192.9524	8.9525	1.9536	Current & New	0.982

Table 4: Test and Descriptive Statistics – KUDA

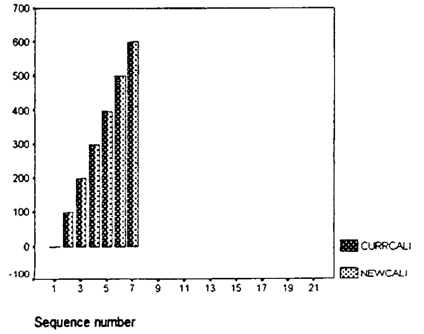


Figure 8: TSPlot for Calibration

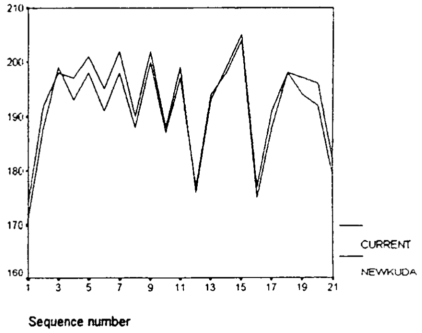


Figure 9: TSPlot for Actual Readings

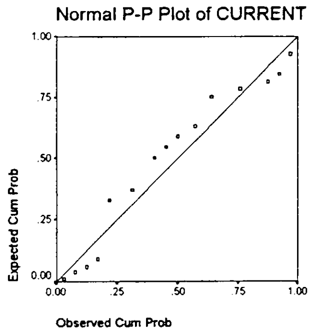

Normal P-P Plot of CURRENT

Figure 10: Normal P-P Plot – Current

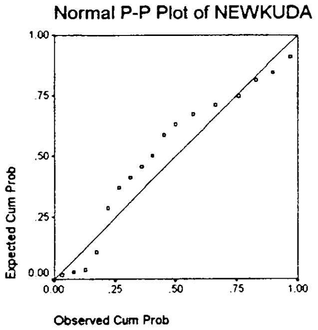

Normal P-P Plot of NEWKUDA

Figure 11: Normal P-P Plot – New KUDA

The software was tested and works excellently. Once the sensor does the reading, the new application software stores the reading in an Excel file. All data pertinent to structure and coordinate of the reading is also captured. But, what happens once the data is collected? At the moment, not much happens with the collected data because the data goes to a piece of paper. But now that we have established communication between the KUDA and the CPU, the data goes directly to the computer (an Excel file). Thus, with the wearable-based system, data analysis can be done on a more continuous basis provided that the right analysis tool is available. We tested the use of PIExpert, which is a program for process improvement. Full discussion of this test is found in another report submitted to PH-M1-B. The success of this experiment represents a great improvement in data collection, data analysis, and process control and monitoring because it will enable proactive analysis and control instead of reactive analysis (Figure 12). The test showed that the integration of the KUDA sensor is feasible. This new system will significantly reduce the time needed to capture the readings and to store them in an Excel file because it avoid the manual data entry step. In addition, the use of PIExpert may lead to a reduction in the number of observations needed. It has been estimated that in addition to the elimination of data entry, there may be a reduction in the actual data collection time of about 26 hours per flow.

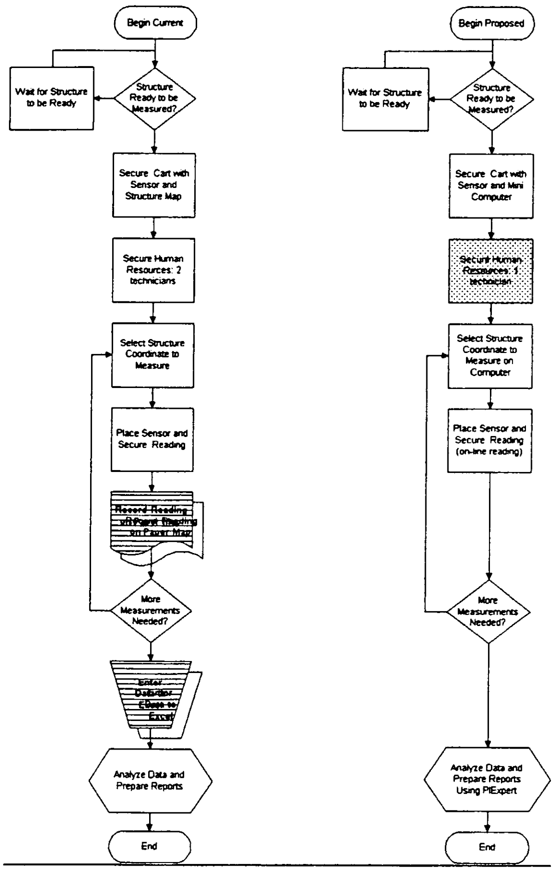


Figure 12: Data Collection and Analysis Process Comparison

Specific recommendations are that:

1. USA SRBARF acquires a wearable unit. Mid Riff Brain seems to be a more robust CPU; however, the MA V model has become available and it is lighter than Mid Riff Brain.
2. USA SRBARF acquires a copy of the PIExpert software. This will enable on-line process control, data analysis, and reporting.
3. Request a demonstration unit from Perkins Engineering (Mid Riff Brain) and VIA to do a test, including the usability test (Phase 1 and Phase 2).
4. Conduct usability test with the technicians using existing MA IV unit (Phase 2). Questionnaire in the Test Plan may need some modifications.

5. OSB USABILITY TEST

The primary goal of this test was to establish the usability of wearable computers when carrying out normal computer functions such as reading text, graphics, schematics, and entering data. The unit used for this test was the Xybernaut's MA IV unit. Other units such as the VIA and MRB need to be tested as well.

The usability test was done in the Operations Support Building (OSB) where a temporary wireless network was set up. The test required the development of two web pages and the use of the Shuttle simulator linked from the KSC main web page. The test called for two different modalities of interaction: 1) For data display → touch screen and heads up display, and 2) For data entry → touch screen using JOT software and super mini keyboard. Hence, two groups were formed, and the order was swapped to reduce learning bias. Acceptance by the users was measured via direct observations and post-test questionnaire addressing four aspects: physical, mobility, data entry, and data display. The actual questions in the order given are shown in Table 5. All the participants were knowledgeable user of a regular PC.

Q#	**Statements**
1	The text displayed on the touch screen panel was easy to read.
2	The video shown on the touch screen was easy to see.
3	The schematics / drawing displayed on the touch screen panel were easy to see and understand.
4	Sounds coming out the touch screen speakers were easy to hear.
5	Typing on the wrist keyboard was easy.
6	Interacting with the touch screen panel with the stylus was easy.
7	The text display on the HUD device was easy to read.
8	The video shown on the HUD was easy to see.
9	The schematics / drawings displayed on the HUD were easy to see and understand.
10	Sounds coming out the HUD speakers were easy to hear.
11	Typing on the wrist keyboard while wearing the HUD was easy.
12	Interacting with the mouse was easy.
13	Reading instructions on paper while wearing the HUD was easy.
14	Entering Text using the wrist keyboard was easy
15	Entering text using the JOT program was easy
16	Scrolling on the touch screen was easy.
17	Overall Interaction with the wearable computer was easy
18	My lower back was comfortable while using the wearable computer.
19	My hip area was comfortable while using the wearable computer.
20	My arm was comfortable while wearing the touch screen on it.
21	The overall weight of the wearable was OK.
22	I was able to comfortably walk, while using the wearable computer.
23	I was able to comfortably climb, while using the wearable computer.
24	I was able to comfortably bend while using the wearable computer.
25	I was able to reach wherever I needed to while I was using the touch screen on my arm.
26	My eyes were comfortable when I read schematics from the touch screen.
27	My eyes were comfortable when I read text from the touch screen.
28	My neck was comfortable while using the touch screen.
29	My eyes were comfortably when I read schematics from the HUD.
30	My eyes were comfortably when I read text from the HUD.
31	My neck was comfortable while using the HUD
32	Overall, I was physically comfortable after using the wearable computer.

Table 5: Ordered Questions

Table 6 shows the frequency of responses for all questions. Overall, it can be seen that 62.32% of the responses were either ***agree*** or ***strongly agree***. Only 8.12% of the responses were either ***disagree*** or ***strongly disagree***. A significant 29.57% of the responses were in the ambivalent area (***somewhat agree, somewhat disagree***) The analysis per aspect will show the areas that caused this ambivalence. From these responses, it can be concluded that overall there is a strong inclination to using this technology, provided that some issues are resolved.

A couple of questions we had from the beginning were whether the responses would be correlated to the participant's weight or gender. It was necessary to establish an answer to these questions because if the technology is adopted, users selection as well as training required must take into account any difference that there might be. Thus, we ran several tests of hypothesis comparing responses across gender as well as weight. Results of these tests are given in Table 7, Table 7: Comparison Based on Weight and Gender

, and Table 8. The actual *paired-t* tests were done on the difference $\delta = \mu_1 - \mu_2$, postulating that there is no difference ($\delta = 0$) as the null hypothesis. The tables show a 95% confidence interval around the mean value of δ ;

hence, if the confidence interval contains the value zero, the null hypothesis cannot be rejected. Failing to reject the null hypothesis implies no evidence of a difference between the two population mean responses.

	Negative	**Ambivalent**	**Positive**
All Questions	8.12%	29.57%	62.32%
Data Display	7.50%	32.50%	60.00%
Data Entry	6.38%	37.23%	56.38%
Mobility	9.09%	9.09%	81.82%
Physical	7.69%	27.35%	64.96%

Table 6: Frequency of Answers - All questions

With respect to weight, we found no significant difference, except in the mobility aspect (Table 7). People with less weight rated the unit in the <u>*disagree*</u> level, whereas the heavier individuals were a lot more incline to say that the unit allow for great mobility. However, even in mobility, the level of difference is not conclusive since the upper limit of the confidence interval is very close to 0 ($-4.26 \le \delta \le -0.07$). The latter is mildly corroborated when we looked at the correlation factor between weight and average response, which shows that there is only a ***weak positive correlation*** ($\rho = 0.275$); i.e. the higher the weight of the user, the higher the ranking of the unit (highest value is the most positive) (Table 8). This result *was expected* because despite the low weight of the unit used, it still looks bulky on thinner individuals. Technology will continue to evolve to a point in which perhaps this will not be an issue any longer. With respect to gender, there is no significance difference either (Table 7: Comparison Based on Weight and Gender

); the correlation analysis also shows that there is only an indication of a ***weak, positive correlation*** ($\rho = 0.240$).

Question 17 requested a perceived easy of interaction, and Question 32 requested a perceived comfort. In these two perceptions, we also investigated if there was a correlation based on gender. From Table 7: Comparison Based on Weight and Gender

, it can also be seen that there was <u>*no difference*</u> on the perceived level of ease of interaction or comfort. However, the width of the 95% confidence interval [4.442 and 5.72 in a (-6,6) range] as well as the correlation factor [0.4 (moderate) with a significance of 0.1] indicate that there ***may be*** some difference, trending towards male users being more inclined to perceive the unit as easy to use and comfortable. Confirming if such difference really exists is important when deciding which technician will use the unit. *Small, medium, large body frame? Male or female? What kind of training should the user be given?* It is recommended that if the technology is implemented, training for small-framed users as well as for female users take into account the slight difference.

Hypothesis Being Tested: $\begin{matrix} H_0 : \mu_1 = \mu_2 \\ H_1 : \mu_1 \ne \mu_2 \end{matrix}$ Converted to → $\begin{matrix} H_0 : \delta_1 = 0 \\ H_1 : \delta_1 \ne 0 \end{matrix}$

where δ = Difference between population means and μ_1 = Average of population below or at 140 lbs. And μ_2 = Average of population above 140 lbs.

ASPECT	MEAN	STD. DEVIATION	STD. ERROR	CI-LOWER	CI-UPPER
Overall	-.4533	1.0248	.4184	-1.5288	.6222
Physical	-.3833	1.4204	.5799	-1.8740	1.1073
Data Entry	-.3700	1.1362	.4639	-1.5624	.8224
Data Display	-.1633	1.1583	.4729	-1.3789	1.0522
Mobility	-2.1667	1.9916	.8131	-4.2568	-7.6559E-02

Hypothesis Being Tested: $H_0 : \mu_1 = \mu_2$, $H_1 : \mu_1 \neq \mu_2$ Converted to → $H_0 : \delta_1 = 0$, $H_1 : \delta_1 \neq 0$

where δ = Difference between population means and μ_1 = Average of Female population and μ_2 = Average of Male population

ASPECT	MEAN	STD. DEVIATION	STD. ERROR	CI-LOWER	CI-UPPER
Gender	-.5780	.8484	.3794	-1.6315	.4755
Q17	0.800	1.7889	.8000	-1.4212	3.0212
Q32	-2.4000	2.3022	1.0296	-5.2585	.4585

Table 7: Comparison Based on Weight and Gender

	WEIGHT		GENDER	
	ρ FACTOR	SIG. (2 TAILED)	ρ FACTOR	SIG. (2 TAILED)
Overall Average	0.275	0.387	0.240	0.453
Q17	- -	- -	-0.316	0.317
Q32	- -	- -	0.493	0.103

Table 8: Correlation Average Response - Pearson Correlation

6. SUMMARY

This effort has explored the state of the art of wearable computers technology, and it has explore its introduction in some areas of shuttle assembly. The tests clearly show that the technology is indeed appropriate for some areas but not for others. It also revealed the strengths and weaknesses of existing commercial units. The use of HUDs is not recommended at this point in time. HUD technology will continue to mature and medical concerns will be addressed.

It is recommended that wearable computers be used at the SRBARF for TPS Thickness measurement, but in a batch mode, so that there is no need to set up a wireless network in an area where explosives are used. Exploring other areas to use this technology is also recommended. Tile water reproofing may be an excellent candidate to fully test next.

Full report of each test presented here has been submitted to the PH-M1-B organization.

ACKNOWLEDGMENTS

Special thanks are due to all technicians and engineers who facilitated and participated in this study. Among these are: Jason Armour, Merle Japp, and David Mandernack from Rocketdyne; Carrie Oyler from IE/HFE USA; David Eckols, Leonard Hutto, Sue Kohl, Leif Morton, Don Noah, and Anil Patel from SRBARF USA; Daisy Correa, Marcia Groh-Hammond, Angel Lopez, Alicia Mendoza, Darcy Miller, Jessica Mock, Luis Saucedo, Kimberly Shanks, Damon Stambolian from NASA. Deep gratitude to the mangers and technicians from OPF 1, 2, and 3 for their support with this effort.