

Process Contracting Limited

Human Factors Consultancy



Human Factors criteria for hand held devices

**With emphasis on devices for maintenance and
diagnosis**

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Summary

This report is based on a report produced for what is now MLS5 in the MoD. It has been found that the topic and material is still relevant, and so it is considered useful to make it available again. Unfortunately, the illustrations have been lost in the intervening period. The sponsorship of (then) ME253 is gratefully acknowledged, as is the assistance from Paul Pearson and Dave Stovell of the Product Design Engineering Dept. at Glasgow School of Art.

The guidance is principally aimed at purchasers of such devices, but may also be of assistance to designers.

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1. Introduction

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2. Operational functions

2.1 **Current and potential functions**

This section identifies current and potential functions for hand held devices and comments on skill aspects. The support functions of communications and manuals are discussed.

Layton [6] has pointed out that it is important to "provide carrots, not sticks" when introducing hand held devices. A number of devices are an encumbrance to the user (whilst being of benefit to others). It is important to try and find benefits to stakeholders directly affected by their introduction.

Rounds data gathering

The introduction of the Psion organizer for collecting data was considered by people interviewed to have reduced skill demands.

It has been said that perhaps the main reason the rounds data is gathered is to ensure that the roundsman has been everywhere. It would be possible to use a different sort of hand held device to address this directly. Video clips of each area on the round or route could be annotated with points to watch/listen/smell for. A number of rounds could be built to concentrate on particular aspects; the degree of 'check off' required would be a function of roundsman training and experience.

The USN has experimented with Virtual Reality wearable computers for familiarization and fire fighting training [7]. Such devices would allow more comprehensive support to rounds..

Meter reading, calibration, test signals

The technology in this area continues to move quickly. Many meter readings are possible from small digital instruments, and hand held oscilloscopes are available. Devices vary in the ease with which some basic aspects have been addressed e.g. ensuring that the correct leads go into the right terminals and that

terminals are protected from the environment.

Like condition monitoring equipment, routes, prompts, procedures and checks have been built into this type of equipment, reducing skill demands and giving greater safety assurance.

CCTV

Closed Circuit Television (CCTV) cameras and camcorders have been proposed for mobile use e.g. to provide the means of improved supervision.

IR cameras for fire fighting

These devices are in service. It would be possible to envisage future devices having up-links to the control room or incident HQ and integration with other plant and system information.

Thermography

IR analysis of mechanical and electrical equipments can be undertaken. There are two levels of skill; a routine identification of hot spots and a skilled investigation.

Diesel engine analysis

Systems are available for the detailed analysis of diesel engine performance, e.g. measuring cylinder pressure in relation to crankshaft angle. These include a number of probes and a hand held computer.

There is considerable research into condition monitoring. Work at RNEC [8] has characterised engine performance using instrumentation from five subsystems:

- charge air system
- exhaust system
- combustion monitoring
- fuelling and power
- lub oil and cooling water

The instrumentation will be used to perform on-line condition monitoring and fault diagnosis using neural networks.

Computer system data analysis

The skill demands of computer system diagnosis is a function of the system BITE facilities and the user interface of the hand held device. Some devices have simple routines with on-line help, while others have had complex codes and no operator assistance.

Vibration analysis

The data collection aspects of vibration analysis should be relatively straightforward, but some people interviewed reported problems with operators not holding the probe at the correct angle, and data collection points and their identifiers being painted over. Probe design could encourage good practice by making it easy to hold at the correct angle.

Gas turbine analysis

Koch [9] has developed a prototype portable system (SAVANT) with KBS operator support and a multi-media interface to perform electronics troubleshooting and combustion monitoring system corrective maintenance.

Bar code reading

The use of bar codes for stores items is increasing. Bar codes have also been used industrially to identify data collection points to save the need to type in the identifier (with the risk of error). The use of a separate bar code reader would be considerably less desirable than having the function integrated into a device. From reviewing the market and the ergonomics literature, there is a strong case for ensuring that the scanner is at the correct angle (see Section 6 - scanners).

Weighing

Some functions that have been considered for hand held devices include ultrasonic level meters (e.g. instead of weighing gas cylinders).

Thickness

Probes can be used to measure thickness e.g. paint.

Some merchant ships are required to do regular surveys of structural thickness using ultrasonic techniques. Hand held computers are used to manage and record the survey.

Communications

Future developments in wireless communications links and communications management open up the possibilities of multi-media communications links on similar lines to the corporate market. Possible system architectures would then allow more immediate command and control links with less voice traffic. Integration of communications and other functions (like some electronic personal organizers now

available) would be necessary for ease of operation and to reduce the number of devices.

The extent of feedback to a control room possible during device use is a function of the communications facilities available and their integration with device operational functions.

Manuals

Some devices have a route or tour loaded into the software which simplifies routine activity. These facilities can also allow the user to vary from the route or to perform off-route tasks, providing flexibility of operation.

The introduction of Interactive Electronic Technical Manuals (IETMs) is likely to mean that some users will have electronic manuals at sea. Research into electronic manuals has been under way for some time. The literature indicates that [10, 11, 12] there are operational benefits in terms of time and error from the use of electronic manuals rather than paper.

There has been a long line of research into the integration of on-line manuals with diagnostic instrumentation and expert systems. This integration could simplify task performance and reduce skill demands. It could be accomplished using wearable or hand held devices.

Integration of logistics aspects can begin at the coal face if the device includes details of spares and their locations.

Devices vary in the extent to which procedures and help are possible. Depending on screen size, graphical aids such as deck plans and compartment drawings/images can be provided.

2.2 Styles of use

There are four styles of use of hand held devices that have emerged during the course of the study. These are:

- personal organizer,
- routine data collection, monitoring, calibration, trend analysis,
- investigative analysis,
- repair.

Personal organizers of the Psion 3a variety are widely used as electronic organisers. When devices with built-in communications links become widely available, it would be possible to see such devices becoming part of the organization's intranet (or extranet).

Routine data collection and monitoring tends to be badly served by the market. There is a need to improve the basic ergonomic

aspects of ease of use and to provide greater operator assistance. In the vibration analysis application, the market for simple data collectors is not there because the customer interest is in analysis facilities at the expense of the unskilled data collection operator.

One view of the future is that this will become part of an integrated condition monitoring approach [13] bringing together data from vibration analysis, lub oil analysis and performance parameters and combining them with data from loggers, maintenance history, trials and visual inspection. This integration is assumed to happen at a computer terminal in the control room or office rather than in the hand held device.

Investigative analysis will become more and more complex as more channels of more types of data can be incorporated into smaller devices. The demands on operator expertise are considerable. The operators are in great demand, and freeing time for training consequently difficult. There are grounds, therefore for increasing the degree of operator support in specific machinery knowledge or in diagnosis. Hobday [14] has found that the human/machine interface is a major factor in the success of condition monitoring systems. The human/machine split in data interpretation and in decision making needs to be carefully assigned - particularly with the introduction of KBS, neural networks etc.

Repair has been the subject of considerable research, and has been the focus of wearable computer demonstrations. The expectation is the integration of many separate facilities. A smart Interactive Electronic Technical Publication (IETP) linked to equipment diagnostics (with a KBS diagnosis aid) provides the operator with the right procedures and information. Operator input (typically voice input on demonstrators) is used to provide additional information. The repair procedure typically includes video clips of removal and replacement actions. Communications facilities include voice, data and video.

Wearable computers have also been investigated for an immersive VR training device for fire-fighting and ship familiarization [7].

3. Context of use

This section examines the context of use and identifies criteria from a user point of view. Where there are relevant standards, these have been identified, but the emphasis is on the 'real' user requirement. The following quote by a user is offered:

"Picture a man hanging like a bat under the plates beneath a leaky diesel, trying to do up a seized bolt which he can't see and can only just feel with oily, slippery fingers, at 0300 in a storm! Under these conditions what the average fitter craves (other than his bed) is a good spanner that fits, not guidance from a computer on what to do with it."

It is now established best practice to examine and document the context of use as part of usability assurance. The context of use embraces:

- the physical environment (here including clothing compatibility)
- the technical environment (e.g. other computer systems)
- The organizational environment.

Each of these environments is examined below.

The physical environment is very demanding

Lighting

The device may be used in poor lighting conditions and backlighting is highly desirable.

Sound

The device may be used in noisy conditions. Some of the devices seen relied on audio feedback (e.g. for membrane key operation) and for alarms. Computer 'beeps' are unlikely to be heard in some of the conditions of use. If audio feedback or alarms are required for the device (and this is quite likely) then devices with

computer beeps should be treated with caution, and the audibility tested.

Temperature

Conditions in machinery spaces are very variable. In a steam ship temperatures can exceed 50 deg C with 100% relative humidity. In some instances temperatures can reduce to freezing - in refit or in a space where little machinery is running when the outside temperature is very low (e.g. Arctic). Condensation is often a problem. Condensed water on the hull plating is obvious, but there is often "rain" from the ventilation, usually when the ventilation coolers are in use.

Assuming a roundsman takes his device with him when visiting "outside" spaces, he may well transit the upper deck which could be like a furnace or a freezer! Thus the device not only has to withstand extreme conditions during its life but also the possibility of a very rapidly changing environment from one minute to the next.

An example from a member of the study team illustrates the environment: his quartz watch (which at the time was only a year old and not prone to inaccuracy) lost 5 minutes one day after he had done rounds. During the rounds he went from inside the main freezers (approx. -18C) to behind one of the main boilers (temp approx. 50C), in the space of 5 mins. His watch appreciated the change to its environment even less than he did!

The device may also be left on top of something very

hot or cold.

Chemicals, Liquids

The list of common liquids found on rounds routes can be very extensive and varied. It will be necessary to compile one for the application under consideration.

A relevant standard is BS EN 60529: 1992 'Degrees of protection provided by enclosures (IP code)', It is necessary to decide on the conditions expected and specify accordingly.

Vibration and shock

The device may be:

- dropped and trodden on
- bashed on hatch coamings, door frames, guard rails
- abused/ misused
- dropped in the bilge.

BS EN 50102: 1995 'Degrees of protection provided by enclosures for electrical equipment against external mechanical impacts (IK code)' addresses this topic. Some manufactures also quote 'can be dropped from x metres onto concrete'. MIL-STD-810E gives drop tests appropriate to manual handling, which have been used by some laptop manufacturers. The standard drop heights given are fairly low - normal carrying heights, but other heights can be used. The study team have been told of incidents of data collectors being dropped through the hatch from one deck to the next; it may be advisable to set the drop height accordingly.

Most commercial equipment manufacturers will not release their specification, but several build to very high standards to minimise returns of defective equipment.

It is widely believed that making an item look like it is not military-ruggedised will lead to it being treated more gently. (There is some evidence for this in the commercial field).

Space restrictions and snagging hazards

Machinery space and other accesses vary widely in their size. Many applications include some extremely constricted spaces that require a lot of climbing or crawling to get around. The likelihood of the box suffering mechanical damage is therefore high if worn on a strap and if used frequently. Another consideration is that of snagging in moving machinery, especially if worn round the neck on a strap. All moving parts are, of course, surrounded by guards designed to prevent capture of fingers and limbs, but thin straps may find their way between guard and machine. Something dangling from a strap is therefore not favoured.

Host computer installation

The host computer and the docking, holstering arrangements for the hand held device need to be suitably rugged.

User experience of present installations reported to the study team was that more attention to the host computer installation is required. Ordinary computer wire and commercially supplied plugs may offer little assurance of long-term reliability. In one installation, the wire did not have a stowage and was usually left dangling out of the computer cabinet, or left lying on top, both of which places left it prone to damage. The connections themselves quickly became ill-fitting and unreliable.

Clothing compatibility is vital and difficult

There does not seem to be any simple solution to the carriage of hand

held devices. Holding the device in one hand while travelling through the ship limits what else can be carried and is a less-than-ideal solution. Straps or belts can snag and the operator may have a number of items on straps or belts already. The users' overalls may already be full with communications devices, tools, pocket books, torches etc.

Compatibility with Personal Protective Equipment is essential and can be difficult.

Technical compatibility may be difficult

There is an active debate within the hand held and wearable computer design community [e.g. 5] as to whether such devices should emulate the desk top and windowing look and feel. A desk top is not an obvious metaphor for a portable or wearable device, and the windowing approach is demanding of processing and display space. Researchers are actively seeking alternatives that suit device use. See Section 7 for further discussion on these alternatives.

However, most users of hand held devices are also users of desk top metaphor PCs - maybe associated with the same task e.g. planning or up-loading data. In this case, there is the risk of incompatible user interfaces between the device and the PC. It will be necessary to check for at least the really important aspects of compatibility, such as the following:

- Function keys.

- Command keys, accelerator keys, macros.

- Navigation keys (e.g. tab, cursor, enter, delete), sequence control keys.

- Numeric entry including error handling.

The organizational structure has an influence

As Black [5] has pointed out, "industrial products with SUIs (Solid User Interfaces) which were once stand-alone devices ... are now being integrated into organizational data handling systems."

When deciding the functionality for a hand held device, it is necessary to

Best practice for ergonomic design of jobs applies to hand held device tasks as much as any other. The criteria to be followed can be summarised as follows:

- Ensure appropriate Allocation of Function to people and

machines.

- Avoid "job design by left -overs" i.e. do not automate that which is easy to automate and give the operator the rest.
- Automation should be the result of conscious design decisions.
- Avoid over, under load.
- Avoid pacing.
- Reflect task priority, frequency in the user interface design.
- Job satisfaction.
- Reflect organization objectives.

Boundaries to consider

New technology could free existing organizational constraints and allow boundaries between on-the-spot activity, control room activity, HQ activity to be moved. For example, data could be sent to a remote expert by e-mail, providing an exchange of experience and expertise.

Benefits and trade-offs

The benefits from replacing paper-based data collection (e.g. reduced errors, better alerting to abnormal conditions, reduced data collection costs) have already been realised. The benefits identified here are concerned with further developments. The factors to consider in assigning functionality include:

- **required on-the-spot** capability; in a lean manned organization, it may be necessary for the person on the spot to be able to make decisions rather than just gather data. If this is the case, then information and support will be required in the device. If data gathering and defect repair can be performed together, then there is the potential to reduce time to repair considerably.
- **operator skill and training** ; operator capability can be enhanced by on-line job aids, expert systems and documentation, or supplemented by links (e.g. video) to the control room, Alternatively, more functions can be centralized in the control room or at an organizational HQ level.

- **quantity of voice and data transmissions;** giving the hand held device more functionality can reduce the need for data up-links or for voice between the operator and the control room. Device capability can be varied to replace voice communications with data links which would reduce workload at both ends of the communication link.
- **job design;** if the operator has the support to perform a complete task, or a number of tasks in any order (without being tied to fixed routes etc.), or reversionary tasks at a local position, then there is greater operational flexibility and more variety in job content.

Operator support and training are changing

"The Trekker [a wearable computer] is designed to allow employers to hire cheap unskilled labour and then use them for complex tasks by cyber-instructing them on the job." T3 Magazine Jan '97

4. Task analysis and criteria for device selection

This section gives a high-level analysis of the tasks associated with hand held devices. It is expected that all of these tasks will need to be done for any likely device. People specifying devices should ensure that any proposed device can permit users to perform all necessary tasks, and that the device meets criteria specified below.

It is likely that the tasks will be done by a number of different people. The skill requirements and requirements for common features (e.g. consistent terminology) will need to take into account the particular users and other systems they use.

T.1 Plan device usage

This task is typically done at a host computer terminal. For data collection, it is likely to comprise selecting routes, inputting procedures, reminders, changes to limit values. For maintenance and repair tasks, it is likely to comprise loading procedures, expected values, test data etc.

It may be the case that the CBM, RCM strategy is being developed or adapted at ship level, in which case, the scheduling of device tasks may need to be worked out,

Criteria to be considered are:

- compatibility with other similar systems
- ease of data transfer
- ease of editing, avoidance of redundant data entry
- HCI usability including prompting, feedback, error

handling.

The skill level of the intended user is an important consideration for this task.

T.2 Prepare the device

This task comprises

- checking that the device is functioning properly, has enough battery life, is calibrated,
- checking that the probes work
- loading in data. Criteria include physical ease of use and error prevention measures.

T.3 Travel with device

This task is demanding on the physical characteristics of the device and its ancillary equipment. When evaluating a device on this task, make sure that all extra leads, probes, storage devices, manuals etc. are taken into account.

Criteria include:

- Can the user carry/pocket/wear all items and have a hand free for the ship, or preferably two hands free?
- Are straps, belts, holsters compatible with clothing and protective equipment?
- Does the device (and ancillaries) represent a snagging hazard?
- How likely is the device to be banged when going through a narrow space or up a ladder?
- If protection relies on a carrying case, what does the user do with the case when operating the device?
- Will the device survive the physical environment?
- Are the weight, centre of gravity, handle design in accordance with guidelines in Section 5?

T.4 Perform operational task

This task has been decomposed into the physical sub-tasks. Aspects relating to specific functions have been addressed at Section 2.

T.4.1 Fix/hold device

The user must be free to concentrate on device functional operation, which means that the device should be securely fixed and not need attention, The fixing should allow for easy operation. A range of fixing methods have been devised in addition to holding the device in the hand, such as wearing the

device, clipping the device on a belt, stowing it in a holster, hanging it up.

Criteria include:

- If the device is supposed to be hung up when in use, is there anywhere to hang it, will it hang the right way up and can it be used when hung up?
- If the device is hand held when in use, will the user run out of hands with probes, device operation, holding the device and a hand for the ship?
- If the device is supposed to be put down somewhere during use (probably highly undesirable), is there anywhere to put it?
- If the device is hung from or clipped onto a belt, or stowed in a holster, does this impede device operation? e.g. it may need a hand to tilt the device so that controls can be operated or for the display to be seen - is this hand available, does the increased viewing distance and awkward angle make the device too difficult to use?

T.4.2 Connect to equipment

Criteria include:

- Are the connectors and terminals rugged enough for repeated use?
- Are they protected from dirt, grease, water etc.? If so, are the connections difficult to make (because of stiffness or because the flaps get in the way)? If the covers are removable, are they captive or will they go missing?
- Is it possible to make wrong connections - i.e. are there physical codes to ensure the right connections? Is there colour coding, labelling that assists correct operation?
- Are sensors fragile? Do they need protective caps - are these captive?
- Is the equipment side of the interface clearly labelled?

T.4.3 Operate device function

For all hand held devices it is desirable that the device can be held and operated without undue compression of the hand tissues.

Brand (1985) [in 15], points out that gripping a hand tool involves pressure on the palmar or pulp surface of the digits. In a typical grip action, a very light grasp will bring every segment of very finger, as well as the thumb and the palm, into contact with the surface. As the grip slowly tightens, the rounded pulp surfaces are gradually flattened so that larger areas of the skin come into contact. With increasingly strong grasp, the most prominent part of the finger pulps become compressed until the whole palmar surface of the hand may be white and bloodless. In the case of hand held devices, the contact with the device - especially the parts used for grip - are likely to be much more localised.

Avoid extended typing on task unless it is certain that the device can be put on a firm surface.

Reduced size keyboards are much harder to use than full size keyboards, and a full size QWERTY keyboard cannot be held in even a 'clipboard' grip. The best approach is to re-design the task so that only short amounts of typing is required e.g. by use of easily-understood codes, menus etc.

Weight is important: Products that are supported by the arms and held away from the body in an awkward position when in use should not weigh more than 2.3 kg. [1]. Hand tools that must be manipulated with precision should not weigh more than 0.4 kg [1].

The user interface should be easy to use (See Section 7):

- Is the sequence of events prompted, is there on-line help where appropriate? If manuals are required, is the text linked to the stage of operation?
- Are there macro keys or other means of avoiding long keying sequences?
- Is error prevention and correction

adequate? **T.4.4 Confirm device operating**

correctly

At the start of device operation, it may be important to ensure that the device is working correctly e.g. that it is calibrated. Is this necessary, and if so, is it easily achieved?

T.4.5 Ensure safe operation

Some device operations may pose a hazard either to the device or to the equipment or system being checked. Is this hazard dealt with? e.g.

- Are there adequate interlocks, warnings, cut outs?
- Are these easy to detect and interpret in a

working situation? **T.4.6 Confirm operation complete**

In many cases, it is important to ensure that data capture has been completed successfully. This should be a simple matter, rather than any lengthy keying sequences. Is there the risk of loss of data?

In the case of calibration activities, some devices insist that the user performs the task within specified limits. This may conflict with the criterion that interactive dialogues have controllable pace (see Section 7).

T.4.7 Perform local analysis

Where local analysis is undertaken, then normal HCI usability criteria e.g. short keying sequences, good prompting, feedback, error handling apply. In addition, it is important to consider the skill level of the intended user, to ensure that the analysis data - and any action to be taken - is readily understood.

T.4.8 Perform local uploading

Local uploading might or might not apply. It might be via a terminal, via a cordless link or into a removable storage device. Criteria relating to connectors and terminals apply here.

T.5 Upload data, report

On completion of the task or round, data will probably be loaded into a host computer from the hand held device. This arrangement may change if the device becomes part of a wireless LAN, but that is likely to be some time away.

Criteria include:

- Is the reporting format compatible with other reports, data exchange requirements etc.?
- Can users obtain data in a flexible format for their own analysis?
- Is there a risk of loss of data?
- Is the host computer user interface compatible with the hand held device (see Section 7)?

T.6 Analyse data

There has been some discussion of the difficulty of interpreting databases of readings; this is an active area for technology such as KBS and Case Based Reasoning. Analysis such as vibration analysis is considered to require considerable skill and in-depth knowledge. The balance between operator support, training and skill levels needs to be addressed in

system design. The extent of analysis at ship level and at Fleet level needs to be considered carefully for each system.

T.7 Stow device and keep it in operational condition

Some devices have docking ports for up loading data and/or re-charging batteries. The port may or may not provide a location for probes, leads etc.

As part of system procurement, it is important to ensure that secure stowage is available for all device elements, including battery chargers etc.

5. Criteria for each type of device

This section supports the graphical checklists given at the front of the report, providing references and qualifying remarks as appropriate.

General criteria for hand held devices

ASTM Standard Practice for Marine Systems F-1166-88 states that the weight and dimensions for portable test equipment should not exceed the following:

Dimensions	Operability, Hand held	
	Optimum	Maximum
Weight (kg)	1.4	2.3
Height (mm)	50	100
Length (mm)	200	255
Width (mm)	100	125

The standard also recommends rounded corners and edges and hinged, permanently attached covers. Instructions should be written in a simple language and printed large enough to be seen in low light.

Types of device

The grip classification scheme devised for this study is based on a review of available and forthcoming products - there does not appear to be an ergonomically based classification scheme as yet, and product labels (e.g. palm top) do not reflect the way that they are held and operated. Wilson [4] has found the same classification problem i.e. that the grip classifications given in the ergonomics literature are based on hand tools

and are inappropriate to hand held computing devices and instruments.

We have classified devices as follows:

- Pistol grip
- Handle/frame
- Open grip
- Clipboard grip
- Portable
- Wrist/hand mounted
- Wearable

Pistol grip

An angle of 15 -20 degrees (ideal 17 degrees) for the pistol grip is appropriate [16]. For devices with a 'pointing' function such as scanning, this feature appears to be highly desirable.

Make sure that the grip (and any controls on it) can be used by either hand.

The first two fingers tend to be the most important in gripping things [17]. If these fingers cannot be used because of trigger controls, then the device has to be gripped by the ring and little fingers - a weaker grip. If this is the case, check the device carefully for fatigue with extended use.

Pistol grip devices tend to be bulky - they are likely to be an obstacle when holstered going through confined spaces.

Handle/frame

Two innovative devices have found solutions to reconciling grip size and device size. Both rely on movement of the control panel to meet the needs of both left and right handed users. This device offers the user the choice of a handle/frame grip or a clipboard grip. The "Read/OK" keys allow single handed operation & grip by either hand. The eyes allow a range of strap arrangements.

Open grip

Small hand held devices tend to be held in an open grip e.g.

calculators, mobile phones, PDAs, many instruments.

No formal scheme to describe different grips was identified. Three types of grip appear to be in use, in increasing order of steadiness.

The first is a grip between the thumb and the finger tips, used for larger palm top type devices. No formal anthropometric data was found to put an outer limit on this, but the ASTM figures given at the start of this section (100 mm optimum, 125 mm max) seem to be the most that could be accepted.

The second sort of grip is between the base of the thumb and the finger tips (i.e. at the distal interphalangeal joint). PeopleSize [18] data gave a figure of less than 94 mm (5th %ile female) as a limit to this grip (data reproduced from PeopleSize with permission of Open Systems Ltd.).

The third sort of grip is between the knuckles (the proximal interphalangeal joint) and the base of the thumb. Data from studies on power tool grips [19] and hand tools [17] indicate that this should be between 50 - 60 mm, definitely less than 70 mm and more than 40 mm, and less than 65 mm.

Many open grip devices can be operated by the thumb of the hand holding the device - typically with the device resting on the distal interphalangeal joint and the metacarpals. There are no dimensions published to define this criterion.

The PARCTAB prototype at Xerox PARC has controls round the edge - a concept that could be expanded to become a chord keyboard (see Section 6). The elegance of such an approach would need to be offset against the potential for accidental operation and the possible encumbrance of a carrying case.

Clipboard grip

Wilson [4] reports that using a "cupping" grasp (rather than an open grip) increases the moment arm and the gives perception that the device is heavier.

The width of a clipboard device is important, but not a standard anthropometric measure or readily derived. Wiklund et al [20] estimated that the distance between the elbow crease/bicep and the curled hand to be in the range 229 - 254 mm for their user population.

Ergonomically designed devices for a clipboard grip give plenty of space on both ends of the device for holding it - unlike a notebook computer which has keys right up to the edge.

Straps have been used on the side or the back of the device to make it easier to hold. One device had a glove stuck on the back for this purpose.

Most clipboard devices fail to achieve a viable QWERTY keyboard. However, such a combination is possible - though not with a full keyboard. See Section 6 for a discussion of this.

Some of the minimal literature on anthropometry for hand held devices has been done using a clipboard type device (7.62 mm deep, 30.48 mm long,

17.78 mm wide) [21]. This examined the use of the thumb for button pressing. Their results included the following:

Dimension	mean	Standard Deviation	5th percentile	95th percentile
Thumb reach at 0 deg	69.5	6.7	57.7	80.3
	62.8	8.2	51.3	76.9
Thumb reach at 45 deg	69.0	6.7	57.7	80.3
	62.3	6.9	53.1	73.8
Thumb reach at 90 deg	67.7	6.9	57.7	76.9
	61.5	5.4	53.1	69.0
Most comfortable angular displacement	55	14.97	33	86
	54	13.59	34	85
Maximum angular displacement	115	10,33	100	132
	115	8.77	107	133
Thumb reach at maximum angular displacement	68.0	7.4	54.6	76.9
	59.0	5.9	49.7	69.0

Thumb anthropometry for males (first line) and females (second line) [21]. measurements in mm or degrees as appropriate.

As Gilbert et al [21] point out, design limits are likely to be determined by the 5th percentile of the population, i.e. 33 - 34 deg angular displacement.

Portable

The standard notebook computer used in office and home environments have been shown to lead to excessive head and neck inclination [22] - detachable keyboards or screens are recommended. Their extended or regular use in less benign environments may well lead to more severe postural problems. An assessment of postural problems should be undertaken if they are to be used.

The most important factors affecting the portability of a device are [1]:

- Weight

- Size
- Centre of gravity
- Moment of inertia
- Handle design (see Section 6).

The recommendations from [1] below do not take into account the problems of an industrial environment (ladders, hatches etc.).

The 5th percentile weight (male and female) for a portable product (one hand carry) is 4.4 kg. (Note that for portable computers, the arbitrary division of 8.5 kg separates the lightweight notebooks from the heavier laptops [22]).

For portable devices to be carried one handed, the maximum dimensions are:

- Length 1000 mm.
- Width 150 mm.
- Depth 450 mm. (for ground clearance)

The centre of gravity should be in line directly below the handle. The torques on the wrist should not exceed 25% of the maximum isometric strength for wrist rotation [1]. The 10%ile limits are as follows:

10%ile forward loading N-m	10%ile rearward loading N-m
1.8	2.8
1.0	1.0

limits for eccentric loading of portable devices [1] for males (first line) and females

(second line)

Moment of inertia has a significant effect on device "feel" [1], and there is a preference for the "feel" when the centre of gravity is toward the bottom of the device, which becomes less important as device weight increases [1].

Wrist/hand mounted

A range of devices are now being devised for use while fitted on the hand, wrist or forearm. Some initial user reaction to the concept has been favourable as it would overcome the shortcomings of things having to be worn round the neck and without the problems of having to carry it in a pocket. Clearly, the capability of such devices will remain limited until pen or voice input has been proven.

Wearable

Wearable computers cannot be dismissed as science fiction. A number of wearable computers have been developed for military maintenance purposes and have received favourable (if informal) evaluations from the USN - for submariners (System 6) and SEALs ('THE WEARABLE').

Discussion on where the host computer of a wearable device might be worn has suggested two options; on the chest in the manner of body armour or worn in a shoulder holster. Both of these would appear to be less obstructive than the normal belt mounted device. It is understood that Reebok is sponsoring research at MIT into power sneakers with a built-in wearable computer which also recovers between 5 and 17 watts of energy expended while walking.

There are no defined ergonomic criteria for either the hardware or the HCI as yet. Points that have emerged during discussions include:

- The wide range of user reactions to the head mounted display.
- When the head mounted display has been moved out of the line of sight, it was knocked off when going through a hatch.
- Some devices seem to have hard angular corners that would dig into the user's back.
- Some devices have many bits and wires, with the

impression of difficult maintainability and easy snagging.

- Routine housekeeping e.g. how to store the device does not seem to have been addressed.

The lack of *product* guidance places a considerable load on the design *process*. Lin [23] has started to devise an ergonomic design process tailored to the need of the wearable computer, with a wearable objects analysis, which was used in the development of the Intimate Electronic Friend. The wearable computer team at the Engineering Design Research Center Carnegie Mellon University have developed a multi-disciplinary rapid prototyping approach [24].

6. Criteria for device components

This section supports the graphical checklist at the front of the report and identifies criteria for typical device components under the following headings:

- User interface.
- Connectors and interfaces.
- Transport and carriage.
- Ancillaries.

In summary, there can be major difficulties with data input, but the detailed aspects of connectors, handles etc. can also make or break a design.

User interface

Hand held, wearable devices pose particular problems for controls and displays because of their small size. Whilst there are problems with small displays [5], the problems are acute for input devices. There is no holy grail [3]. Speech input has restrictions and a number of writers have stated [e.g. 3] that the

present state of hand writing recognition is inadequate. QWERTY keyboards are usually too large for convenience or too small to use.

The Display Screen Equipment (DSE) Regulations exclude portable equipment only if it is not in prolonged use. Guidance on "prolonged" is given. ISO 9241/ BS EN 29241 / BS 7179 is the standard that underpins the Regulations. Most hand held devices differ considerably from the hardware assumed in ISO 9241, and so there needs to be an emphasis on risk management.

The Provision and Use of Work Equipment Regulations are very wide-ranging and would include hand held devices under most circumstances. Ergonomic requirements are given in BS EN 614-1 ('Safety of machinery - Ergonomic design principles. Part 1. Terminology and general principles'. 1995), which specifies a set of design activities and criteria. The standard It is much more wide ranging and directive than its title implies. It states 'hand held equipment shall have the appropriate dimension, weight, balance and shape for the anatomy of the hand and shall allow the operator to use natural body motions during its use. Operation by both left and right handed operators shall be considered, particularly for hand held equipment.'

Display

Is the display large enough to display the most detailed display format? Does it have sufficient resolution?

For diagnostic devices the most demanding format is likely to be a spectral analysis graph. For on-line manuals, the

presentation of schematics would appear to be a daunting challenge.

A number of commercial devices increase the amount of information presented by using small type with small spacing. There are well-established standards (e.g. Def Stan 00-25) for character height and spacing which should be followed.

Alarms, audio, speech output

Some tasks require that the device can display one or more alarms e.g. if either the device or the plant is in or near a dangerous condition. Space and power constraints can introduce difficulties for alarms in hand held devices. Some devices seen by the team have had inadequate alarms, including very quiet beeps which were hard to hear in office conditions, and the use of video invert or flashing on an LCD display, which was hard to read when looking at the display. There are standards for alarms, and - certainly where plant safety is in any way involved - there are no ergonomic or safety grounds for excluding hand held devices. For many devices, good alarm design has been achieved by using traditional indicators rather than LCDs or modern technology

Audio feedback is a feature of some devices. It is necessary to ensure that these will be heard over the ambient noise (typical figure is 15 dB above ambient).

As yet there are no standard tests for synthetic speech output and tests for voice intelligibility are inappropriate if the speech is synthesised rather than digitised and may be inappropriate for digitised speech. Testing in representative conditions is recommended.

Keyboard

Buttons, keys or touch pads need to give tactile feedback to the operator. Beeps etc. are not sufficient - you can't hear them down below. Keys etc. need to be big enough for ham-fisted operators wearing gloves to accurately and easily enter data (see below). Displays need to be back lit so that the numbers etc. can be clearly seen in poor lighting conditions.

An adequate keyboard can be a major problem for hand-held devices.

Operation	Min Size (mm)	Preferred Size (mm)	Max Size (mm)
Bare handed	10	14	19
Gloved	15	22	
Preferred edge to edge spacing is 6.5 mm			

Def Stan 00-25 Part 10 gives separate key size and spacing - rather than the usual approach of stating pitch.

The consensus in the literature for the types of device being addressed is a keyboard pitch of 19 mm. This figure is widely supported (e.g. the work of Taylor on aircraft keyboards).

As Wiklund et al [20] point out, a standard size QWERTY keyboard is too wide to allow users - especially those with short arms - to comfortably grasp/cradle the terminal (see 'clipboard grip' above). They consider a keyboard with 13 keys at 17.8 mm spacing (device 231 mm wide) to be viable - they found that there was a preference for slightly reduced key spacings for typing with one hand. The study team found a device (by Belgravium from Bradford) to have a 10 key wide QWERTY keyboard (data entry does not require a full office

keyboard to ISO 9995) with a key pitch of 20 mm and overall width of 238 mm.

Wiklund et al [20] found that keyboard size affected typing speed even for the worst typists in their study, and so keyboards that are too small cannot be defended on the grounds that users are not touch typists.

Wiklund et al [20] also found that touch screens are not an adequate substitute for a proper keyboard - even when the touch screen 'key' spacing is the same as a full size keyboard, Keyed entry of numeric and alphanumeric data on portable devices, when the user was walking or standing, was faster than either touch or stylus entry [4].

Membrane keys are unlikely to be satisfactory, given the difficulty of providing adequate feedback.

Alphabetic entry using numeric keys (e.g. number + shift key etc.) is obscure and unlikely to be usable.

'Chord' keyboards (e.g. 'Microwriter', courtroom palantypes) achieve alphabetic entry by multiple simultaneous key presses.

The market for these devices is very unstable, and products have come and gone on a regular basis. The evidence is that a well-designed chord keyboard can achieve good typing speeds with moderate training demands. They would not be suitable for a device that might have occasional users.

Numeric keypads should be 'telephone' layout rather than 'calculator' layout (See Def Stan 00-25 Part 10). "If a numeric keypad is offered as part of a portable computer, every effort should be made to provide full-size keys." [25] (i.e. 19 mm). (Note:

this is slightly larger than most calculators and mobile phones, which are typically 16 mm).

Pointing input device

The range of small pointing devices is continually widening. For the small screens usually associated with hand held devices, fairly crude performance may be acceptable. For a full-performance equivalent to a mouse, conformance to ISO 9241 Part 9 should be sought (whereby the supplier will have conducted tests to demonstrate equivalent performance to an established device).

Def Stan 00-25 does not address the small pointing devices now becoming associated with hand held devices.

An ARPA prototype wearable computer uses a rotary dial and pushbutton for menu selection as a mobile alternative to a mouse.

Pen, speech input

Pen input is currently offered on a number of PDAs (Personal Digital Assistants). Some of these require special pens; our study team broke the pen for an otherwise rugged computer, and so the stowage and robustness of such pens should be checked. The robustness of the screen being used for pen input should be checked, both for normal use and for survival in the environment e.g. grease and dirt.

As of 1995 there is widespread scepticism about the use of pen input for handwriting recognition [e.g. 3]. There are no established standards for handwriting recognition. Anecdotal from users of PDAs is mixed - such devices usually have a learning element. The user also learns to write in a

way that will be recognized.

Def Stan 00-25 gives dimensions for stylus or light pen as length 120 mm - 180 mm (min - max) and diameter of 7 - 20 mm.

Speech input is more mature than hand writing recognition. As installed on office PCs, some people find it satisfactory. There are standards for recognizers based on a corpus of spoken material. The effective operational accuracy and user tolerance depend heavily on the design of the dialogue and the task requirements. If adopted, speech recognition - particularly the dialogue design - should be tested.

Other controls

Black et al [5] have pointed out that knobs, sliders provide intuitive operation with built-in feedback and which are amenable to imaginative solutions. No specific guidance was found by the study team - testing would appear to be necessary for assurance of usability.

Device testing

Many devices have built in testing facilities, ranging from battery checks to calibration tests. Confirm by inspection that the device testing user interface is simple to use.

Connectors and interfaces

Scanners

For pointing the scanner comfortably, an angle of 15 -20 degrees (ideal 17 degrees) for the pistol grip is appropriate [16].

Probes, input and signal connectors

A number of devices have probes and other input devices. The principal type of probe investigated was the accelerometer probe for vibration analysis. It is a good example of the importance of attention to detail. Points to note include: A range of probe lengths is necessary to allow measurements to

be made in small gaps or from a distance (e.g. because of a guard).

A magnet to clamp the probe onto the machinery being monitored avoids the problems of errors due to variable pressure from a hand held probe. A

small groove in the centre of the magnet allows it to be securely positioned on edges e.g. motor cooling fins. The magnet - when clamped onto the device - allows the probe to be carried as part of the device rather than separately.

The cable between the probe and the device needs careful handling to avoid it becoming snagged. Suitable breakaway connectors may be useful.

Buttons on probes to activate logging are very prone to accidental operation, but can sometimes be useful to investigative specialists.

Peripherals

Some devices - particularly wearable computers - have devices separate to the main computer. Whilst conceptually elegant, most of these devices seem to have a "snakes' wedding" of cabling which may offset any benefit from re-locating the device. Careful testing would seem advisable.

Data uploading

Is it possible to use wireless data transmission? Many devices have IR or radio links, which are much less likely to be damaged.

Some form of ruggedisation is certainly called for. A man on rounds will connect and disconnect once per hour at least, therefore a minimum of 24 connections/disconnections per day, 9000 in a year. Plugs and sockets also fill up with gunge if left unprotected and of course are routinely handled by people with oily hands, hence the cables and connectors need to be made of materials capable of withstanding attack by all kinds of contaminants. The battery charging connectors must not be forgotten either. Frequent charging of the device's

batteries may be required if it is to perform properly.

Transport and carriage

Cases, flaps, covers

Black et al [5] have found that cases, flaps, covers can interfere with usability. If these are necessary to protect the device, then it is necessary to ensure that they do not interfere with usability. This will require testing in a representative context.

Clearly, cases that need to be removed and put somewhere during operation of the device are to be avoided.

Many devices (especially pistol grip scanners) come with a holster. Some of the holsters have a leg strap as well as a waist band. Pistol grip devices when holstered may well be considered a snagging hazard and may be damaged by ladders etc.

Straps

Strap design can have a major impact on usability. During carriage, a strap should allow the user to cradle the device below the elbow [1]. At the same time, the user should be able to rest the product against the hip and use the forearm to provide stability while walking. To satisfy the needs of both tall and short users, the length of the strap must be adjustable. If the distance

between attachment points on the product is approximately 450 mm, the maximum strap length should be at least 1200 mm [1]. a minimum strap width of 40mm is recommended for products weighing up to 6 kg. for heavier products, a semi-rigid collar that fits across the shoulder is suggested [1]. The strap width should not exceed 76 mm regardless of product weight [1].

Straps can be used to simplify device usage in a number of ways, including hands-free operation.

For some tasks, it is an advantage that the device can be hung up by its strap during use. Check by inspection that the device can be hung up securely and can be read and operated when hung up (some devices hang up upside down).

Some devices have belt clips or carrying cases that allow the device to hang from the belt when not in use (or when probes or scanners are being used). A leg strap would reduce this risk, but would make it harder to fix/release the device or to check that readings have been made correctly by lifting up the device while still clipped.

Handles

Consider all the different uses that the handle will be put to. If the device is to be hung up by the handle, ensure that the handle shape will allow stable suspension. If the device is to be held by the handle when in operation, can the handle be used by either hand?

A well-designed handle allows the user's wrist to remain straight during product use [1].

Recommended dimensions [1] are:

Minimum handle length 100 mm., 115 mm for portable devices.

Handle diameter for a power grip 30 - 50 mm. (Schneider [16] considered 48 x 25 mm to be ideal for a handle/frame device).

Handle diameter for portable devices 20 - 40 mm. If a product is carried mostly by men, then a minimum diameter of 20 mm is recommended. If carried by women, then the minimum handle diameter should be no less than 25 mm. (Men use a hook grip, because men tend to be wider at the shoulders than the hips, while women use a power grip as they are usually wider at the hips than at the shoulders).

Handle diameter for a precision grip 8 - 16 mm.

Required clearance around handle if gloves are not worn 30 - 50 mm. If gloves are worn, then 55 - 85 mm.

When forces must be applied to a handle, its surface should be textured with a fine groove-like pattern to keep the hand from slipping [1]. While a small amount of texture has been shown to be beneficial, large or deep groove patterns place too much localized pressure on the soft tissue of the hand and can lead to abrasions if the handle is held tightly [1]. Do not use deep contours on handles. They will not match the finger patterns of most users [1].

For portable devices handle design is very important [1]. Poor

handle placement can be equivalent to increasing product weight by as much as 60%. Good handle design may increase the amount of time that users can carry a 6 kg product by as much as 20%.

Ancillaries

Batteries

Are the batteries compatible with other batteries used by the same user group e.g. for torches, cameras?

Is the battery life compatible with an extended usage period? Is the type of battery affected by 'battery memory', and is this taken into account when estimating life?

Can the battery be changed easily when the device is in use? - when the user is on task?

Batteries often represent a significant proportion of the device weight - are the batteries placed near the grip location to give a balanced product with centre of gravity in the right place (see Section 5)?

Commercial chargers need ruggedising to make them more reliable in a marine environment.

Data storage

Similar questions to batteries:

Is the data storage the same as that used for other devices, or will special stocks have to be held?

Is the amount of storage compatible with a demanding usage period?

Can stores (disks, flash memory cards etc.) be changed when the device is in operation? - when the user is on task?

7. User interface design guidelines

This section addresses the Human Computer Interaction (HCI) aspect. The approach taken is give a brief indication of general HCI requirements that would apply to any system and to highlight aspects directly related to the small display likely in a hand held device.

Three sorts of guidelines are presented:

- Principles of software ergonomics, linked to health and safety guidelines and applicable to all sorts of computerised devices. These guidelines are statements of design intent.
- Guidelines relating to on-line manuals, as there have been recent developments in this area
- Guidelines relating to HCI design - design standard in nature, and concentrating on the specifics of hand held devices.

Principles of software ergonomics

The principles of software ergonomics apply to hand held devices as much as to any other software based work equipment. Because industry standard HCI guidelines are more difficult to apply within the constraints of a hand held device, it is more important to seek assurance that ergonomic design principles have been followed. The principles can be summarised as follows:

- Suitable for the task, minimum information presented, information and controls should reflect priority, frequency of use.
- Dialogue should be self descriptive, immediately comprehensible, clear and unambiguous
- Controllable pace and direction

- Consistent symbology, layout, conforms with user expectations,
- Error tolerant dialogue, avoid inadvertent operation
- Adaptable, with individualisation facilities
- Suitable for learning, easy to use
- Control/Display compatibility
- Match to illumination
- Provide feedback

Documentation guidelines

Hand held devices are likely to be used for presenting on-line manual information - perhaps tied in to the diagnostic procedure and any diagnosis computing in the device. There is a BS that may well apply to this; BS 7830 'Guide to The design and preparation of on-screen documentation for users of application software'. This is a sizeable document (over 100 pages) which has significant requirements for the design process i.e. the documentation should be covered by a Human Factors plan which meets the standard. There are also design content guidelines - mostly compatible with general Human Factors guidelines, and assuming a full-size VDU.

Of specific relevance to hand held devices with both an instrumentation and a documentation role is the guidance on the integration of application software and its documentation. This gives requirements including:

- The need to decide on the "look and feel" for the documentation in relation to the application, the operating system and other products in the same suite,
- It should be obvious to users when they are viewing the application and when they are viewing on-screen documentation - some presentation device should make this clear.
- The need to manage windows for the application and documentation (e.g. information needed persistently should remain displayed and should not disappear).

HCI guidelines

Consistency between the hand held device and the host computer - or other systems used by the operators - needs to be considered. Such consistency applies to command keys

such as carriage return, enter etc., function keys (e.g. it may be necessary to use F1 for help).

Def Stan 00-25 Part 13 has a comprehensive set of guidelines for HCI design. The objectives set out apply to hand held devices as much as to VDTs.

The use of complex windowing displays is likely to be inappropriate for many ME tasks particularly given the small display space likely in a portable device. This is likely to be a live issue in the near future, as Windows CE™ starts to reach the market. This is a version of Windows 95™ for hand held computers (see illustration below).

Whilst Windows CETM may prove to be suitable for occasional office tasks, it is not necessarily optimal for industrial portable computers.

Layton [6] has pointed out that many office computer conventions are inappropriate to data collectors. Conventions such as "new, open, save, save as" may lead to errors to operators unfamiliar with the concepts and are inappropriate to the task of data collection.

Rekimoto [26] has found different limitations with GUIs and desktop metaphors in wearable computers. He has developed the concept of Augmented Interaction whereby the computer is to some degree spatially aware. This may be achieved by placing barcode-like signs at strategic points which are automatically recognised by the computer from the CCTV image. He points out that interaction between a person and a desktop computer is isolated from the real world, whereas in Augmented Interaction metaphor the user can interact with the real world and the computer together..

Keyed entry vs. menus and touch screens: For frequent entries, key sequences are learned and remembered and are faster than other input mechanisms.

Design the task to avoid data entry by keyboard (or handwriting recognition) wherever possible. In many situations entries in form fields are standard and can be more accurately and quickly picked from a menu [6].

The number of menu options and trade-offs between dialogue breadth/and depth are likely to be different for a hand held device than for a desk-top computer terminal There are some specific concerns to be addressed:

- Excessively long keying sequences because of limited control/display space. These are likely to lead to increased errors [27] and user frustration.
- Cryptic menu codes because of limited display space.

- Awkward control or soft key alignment with the display because of size constraints or irregular device shape.
- Obscuration of display or control elements by the hand or body.
- Mode keys which can lead to slower and more error-prone usage [28].

The important aspect to check [27] is that the menu organization matches the user's mental model.

Some devices have interactions that do not handle errors well, resulting in the need for very careful input keying. When the data being entered is linked to safe plant operation (e.g. entering limit values into a SCADA system) error checking and a review facility are important.

8. Standards

The following standards have been cited in the report as having some application to the ergonomics of hand held devices.

BS 7830 Guide to The design and preparation of on-screen documentation for users of application software.

ASTM Standard Practice for Human Engineering Design for Marine Systems, Equipment and Facilities, F-1166 - 88

BS EN 60529: 1992 'Specification for Degrees of protection provided by enclosures (IP code).

BS EN 50102: 1995 'Degrees of protection provided by enclosures for electrical equipment against external mechanical impacts (IK code)'

ISO 9241/BS EN 29241 'Ergonomic Requirements for Office Work with Visual Display Terminals (VDT's) (Parts 1 to 14 are in varying stages of production).

NES 626 'Control and Surveillance Equipment for Plant and System Installations' Issue 2 April 1991.

Def Stan 00-25 'Human Factors for designers of equipment'

- Part 10 Controls
- Part 13 Human Computer Interaction

MIL-STD-1472 D 'Human Engineering Design Criteria for Military Systems, Equipment and Facilities'

BS EN 614-1 'Safety of machinery - Ergonomic design principles. Part 1. Terminology and general principles' 1995.

MIL-STD-810E Environmental Test Method Standard for Environmental Engineering Considerations and Laboratory Tests July 1983,

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