PEARSON NEW INTERNATIONAL EDITION

Engineering by Design

Gerard Voland

Second Edition

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the Orbiter about the thrusters' operation throughout the flight and then provided information in English units to the craft's navigational system. Unfortunately, the information generated by the computer should have been provided in metric units. Given incorrect data with which to work, the navigational system directed the Orbiter along a flight path into the Martian atmosphere that was too low, resulting in the loss of a $125 million spacecraft.

For some goals, it is understood that they should be achieved completely (e.g., the goal of safety); that is, the corresponding specs are simply 100 percent achievement of these goals. Other goals (such as lightweight or minimum cost) must be defined in quantitative terms so that one has specific targets at which to aim when trying to satisfy the goals and so that one can measure the degree to which the goals have been achieved. For example, the corresponding specs for "lightweight" and "minimum cost" might be "less than 25 pounds" and "less than $1,000," respectively.

Specs may be of several different types:

- **Physical,** including space allocation or dimensional requirements, weight limits, material characteristics, energy or power requirements, etc.
- **Functional or operational,** including acceptable vibrational ranges, operating times, and so forth.
- **Environmental,** such as moisture limits, dust levels, intensity of light, temperature ranges, noise limits, potential effects upon people or other systems that share the same environment, etc.
- **Economic,** such as limits on production costs, depreciation, operating costs, service or maintenance requirements, and the existence of any competitive solutions in the marketplace.
- **Legal,** such as governmental safety requirements, environmental or pollution control codes, and production standards.
- **Human factors/ergonomics,** including the strength, intelligence, and anatomical dimensions of the user (see Section 5 for a fuller discussion of the use of ergonomics in design).

Constraints can force us to use system characteristics creatively and effectively in the development of an engineering design, as shown in the next example.

Pulse Oximetry: Measuring the Oxygen Content in Blood

Working within constraints can help to inspire engineers to develop solutions in which these constraints are used to advantage. For example, the need to measure the amount of oxygen in a hospital patient's blood noninvasively, continuously, and without pain led to the development of pulse oximeters.[16] (Notice that these goals must be achieved completely; that is, the specs correspond to 100 percent achievement of each goal.)

First developed in Japan, pulse oximetry was later commercialized in 1981 by Nellcor, Inc., a medical equipment firm in California. In this technique, a sensor is attached to the patient's finger, toe, nose, or earlobe. A detector then measures the amount of red light from a diode that is transmitted through the skin. More light will be absorbed by dark-red blood that is relatively low in oxygen, whereas more light will be transmitted through blood that is rich in oxygen and bright red. Thus, a blood variable (color) that depends upon oxygen level is used to real advantage.

Pulse oximeters, now used in hospital operating rooms and intensive care units, have reduced the fatality rate of patients under anesthesia. In addition, fetal oximeters are now under development that could prevent oxygen deprivation (leading to brain damage) in babies during delivery.

It is the responsibility of the design engineer to identify—sometimes through exhaustive research—all of the constraints or boundaries that must be satisfied by a solution. Otherwise, a design may be developed that is illegal, hazardous, or infeasible.

5 Ergonomic Constraints in Design

Designers often take advantage of the properties of the human body to develop very creative and effective solutions to problems. For example, the circuitry in a touch-sensitive lamp detects the change in electrical capacitance that occurs whenever a person comes in contact with the lamp; the capacitance of the user's body is added to that of the lamp itself, and this change can be used to trigger an adjustment in the light setting.

Similarly, remote ear thermometers measure the person's temperature by detecting the infrared radiation (i.e., heat energy) emitted from the eardrum without coming in contact with—and possibly damaging—this very delicate part of the body.

Ergonomics (sometimes referred to as "human factors engineering") focuses upon the variations that exist among different human populations and the effects of these variations on product design decisions. Ergonomic data often represent critical design constraints or quantitative specifications

16. See Pollack (1991).

that must be achieved if the safety, productivity, health, and happiness of the designated user population for a particular product, system, or process is to be enhanced.

People can differ broadly in height, weight, intelligence, age, physical abilities, and many other ways. Such variations in the client population for which an engineering solution is developed must be carefully reflected in the design itself. After all, if an automobile seat were not adjustable but only designed to accommodate the "average" man in terms of height and weight, it then would fail to satisfy the needs of most other people. User characteristics that may be important to the success of an engineering design include

- visual acuity
- hearing discrimination
- hand-eye coordination
- reaction time
- sensitivity to temperature, dust, and humidity
- reading skills

The following incident[17] illustrates why human factors should be included whenever a solution to a problem is prepared.

The Sinking Boat

A group of officials from the foreign service of a Western government were scheduled to visit their embassy in a southeast Asian country. Plans were made by a member of the embassy for their visit; these plans included a chartered canal-boat tour of the capital city's business district. Each day this boat carried ten people along the canal routes of the city without incident.

Unfortunately, when the boat left the dock carrying the five visitors along with four other foreign service workers and the driver, it began to sink. All those aboard the boat safely swam to shore, where they were helped by the local citizenry.

Why did the boat sink? It had been assumed that the boat could transport ten people since it did so on a daily basis. However, the Western visitors and most of the others aboard the boat were substantially heavier than the natives; their combined weight was beyond the capacity of the boat to support. One human factor—weight—led to this accident.

During the past 40 years, much effort has been expended to collect and evaluate data describing the variations among human beings. Some of these data are anthropometric—that is, they focus upon the variations in size and

17. Kepner and Tregoe (1981).

proportion among people. Other data describe the variations in people's relative physical abilities (e.g., endurance, speed, strength, accuracy, vision, and hearing), based upon physiological and anatomical knowledge. Similarly, psychology can provide understanding about our abilities to acquire, learn, and process information. All of these data can be used to formulate important ergonomic constraints for an engineering design to ensure that it will satisfy the needs of its intended user population.

5.1 Anthropometry

As noted above, anthropometry focuses upon the variations in the sizes and proportions of people. Much of these data have been tabulated in the form of percentiles, that is, percentages of people who are at or below a particular value. For example, the 50th percentile for men's heights corresponds to the medium value: 50 percent of men in the sample population lie at or below this height, and 50 percent lie above this height. Similarly, the 95th percentile would correspond to a height above which only 5 percent of the sample population were found.

The sample population for anthropometric data necessarily is based upon specific sample sets of people who have been measured and tested in various ways. These sample sets usually are assumed to be representative of the population as a whole. However, the engineer should be careful to note the sample set(s) upon which anthropometric ranges are based in order to ensure that there is a correspondence between the sample and the intended user population of a particular design. For example, data based upon samples of law enforcement personnel may be skewed or biased in some manner since police officers often need to satisfy both minimum and maximum requirements of height, weight, strength, education, and other attributes; it would be inappropriate to describe the general public with such data.

Figure 4 illustrates the form in which anthropometric data are sometimes presented, indicating a series of measurements at the 97.5 (large), 50 (median), and 2.5 (small) percentiles. A product designed for people at the 50th percentile may be unsafe or difficult to use by those people who lie at the extremes of the population (the very tall, the very small, etc.). However, a product designed for use by everyone may not be satisfactory for anyone because it is too imprecise, ill-defined, or unspecified. The question then arises: for what population range does one design?

The answer depends upon many factors: the degree of specificity with which the user population can be defined (e.g., the elderly, children, athletes, those working in a particular trade or profession), the expected application or purpose of the product, cost constraints, and so forth. In general, however, one usually focuses upon the following ranges[18]:

Civilian populations: 2.5–97.5 percentile (95 percent of population)
Military populations: 5–95 percentile (90 percent of population)

18. Diffrient, Tilley, and Bardagjy (1974).

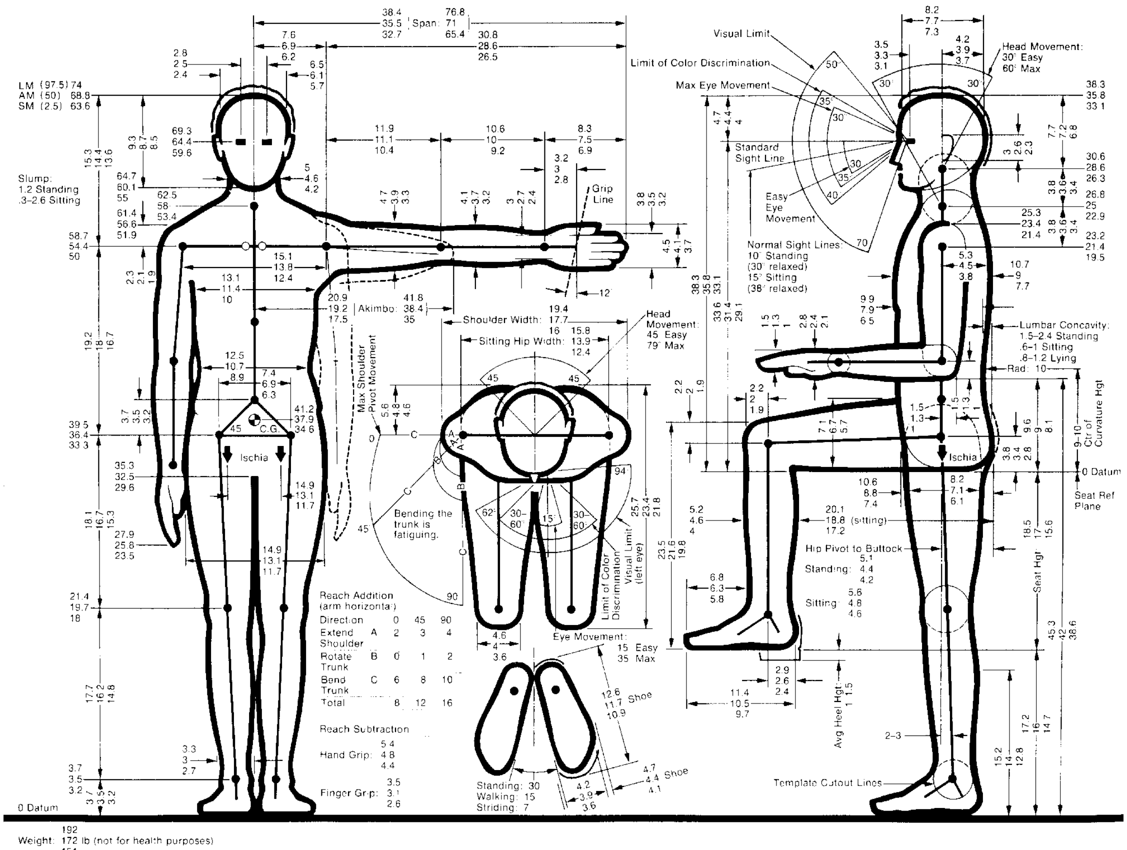

FIGURE 4 Anthropometric data (distances in inches) for men at the 97.5, 50, and 2.5 percentiles. *Source:* Diffrient, Tilley, and Bardagjy, *Humanscale 1/2/3 Manual,* Cambridge, MA: The MIT Press, copyright © 1974. Reprinted with permission.

In other words, a product intended for a military population is usually designed so that all people lying between the 5th percentile and the 95th percentile will be able to use it. The product then is not expected to be used by those lying outside this range (e.g., in terms of height, very short or very tall people would be excluded from the target population).

Obviously, anthropometric data should match the expected user population(s) of a product[19]—e.g., if one is designing a baby carriage, then one should consider data that describe variations among infants in the intended age range rather than children of other ages.

In addition, data should be current for changes do occur among human populations as time goes by (e.g., the average height of a population can

19. Middendorf (1990).

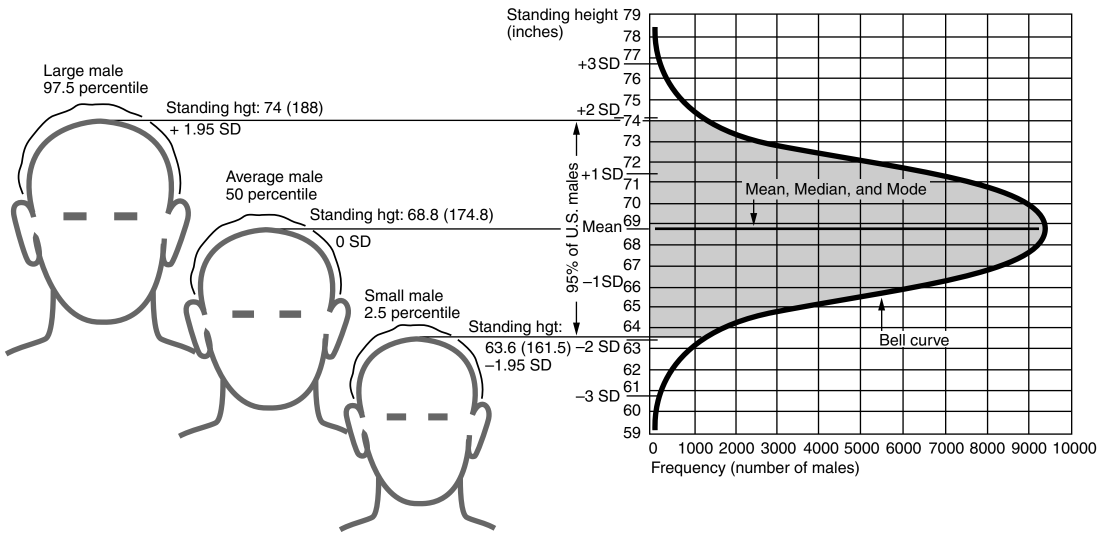

FIGURE 5 Uniform variations in male heights about the 50th percentile. *Source:* Diffrient, Tilley, and Bardagjy, *Humanscale 1/2/3 Manual,* Cambridge, MA: The MIT Press, copyright © 1974. Reprinted with permission.

increase by approximately 0.3 inches every 10 years, resulting in a significant difference over a 50-year period).

It is also important to recognize that human populations often do not vary in a uniform manner. Body heights and lengths do vary uniformly since they depend upon bone structures (Fig. 5). However, weights, widths, and girths may not vary uniformly throughout a population since these measurements depend upon age, amount of fat, musculature, and other factors that may diverge widely (Fig. 6). Although variations in height occur symmetrically about the 50th percentile, variations in weight are asymmetrically distributed about this point. (For an example of anthropometry in design, see Case History 9 *The Ergonomically Designed Lounge Chair*.)

5.2 Human Capabilities and Limitations

When designing a product, system, or process, one must recognize that there are certain abilities and limitations commonly associated with human behavior. These include the time necessary to respond to certain stimuli, the accuracy with which particular tasks can be completed, and the ability to recognize visual, auditory, and tactile stimuli.[20]

All systems involving feedback require a time delay or response time during which (a) the input signal(s) are processed, (b) the appropriate

20. Baumeister and Marks (1967); Middendorf (1990).
21. Voland (1986).