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Task Allocation and Analysis of Common Manufacturing Processes for Humans & Robots

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Abstract

The objective of this paper is to provide a data base to assist in task allocation between humans and robots and to analyze some common manufacturing activities. To accomplish this, the capabilities and limitations of humans, as well as the characteristics of robots, are discussed. General guidelines are offered for the process of task allocation between humans and robots. A definition of task analysis is given and several common manufacturing processes are described. In the task analysis, a determination of those traits required by a human or robot to perform the given task are described. Also given are the results of an investigation into the type of robot capable of performing a given manufacturing activity.

Introduction

From the time of industrial era and the invention and use of machinery, entrepreneurs have been concerned with the optimum assignment of work between humans and machines. Work was studied in relation to man and machines. The first attempt in attaining this objective was made by Fitts.[20] The Fitts list compares the relative strengths and weaknesses of humans and machines. With the advent of robots, the concern was shifted to the best allocation of tasks between humans and robots. A robot time and motion (RTM) method was devised for robot work measurement to compare robot and human task performance.[22] The capabilities of robots and humans were reviewed with a job and skill analysis approach, with the objective to optimize robot's task-performance and specify tasks appropriate for robots.[21] A general framework of a skill analysis approach to robot task performance was explained by Nof and Fisher.[21] A classification scheme of robot structure and size was covered along with a summary of industrial robot capabilities. In addition methods for industrial robot system analysis were examined and compared.[8] A guideline was established to assist in choosing the correct robot for performing a task most productively.[24]

This work's aim is to provide a data base of human and robot capabilities for analyzing and allocating some common manufacturing activities. To achieve this objective, the capabilities and limitations of humans are presented. Robot definitions, categories and characteristics are given in the next section with most commonly available specifications. In addition to presenting a definition of task analysis, different manufacturing processes are described. A detailed analysis was done to determine those traits required by a robot or a human to perform the tasks. Also given are the results of an investigation into the type of robot which can perform a given manufacturing activity. The process of task allocation between human and robot is defined and general guidelines are offered.

Human

In order to allocate tasks, one must be aware of the characteristics of the components in the system to which tasks will be assigned. With this in mind, this portion of the paper will discuss the characteristics of the human. These characteristics will be divided into several categories in which the capabilities and limitations will be discussed. Areas that will be covered include physical characteristics, central processes, senses, environmental stimuli, training, social and psychological aspects, and individual differences.

Physical Characteristics

Body: Damon, Stout, and McFarland[6] reported the results of anthropometric studies conducted between 1928 and 1962 on U. S. civilians and military personnel. One dimension measured was stature, which is defined as the vertical distance from the ground to the top of the head while the subject is standing straight and looking forward. The overall range (the smallest value for the 1st percentile and the largest value for the 99th percentile) is 60.8 to 76.2 inches (154.4 to 193.5 cm) for males varying in age from 16 to 81. The overall range for the stature of females age 16 to 79 is 54.8 to 70.7 inches (138.4 to 179.8 cm) which includes studies reported by Van Cott and Kinkade[25] on U. S. and Canadian civilian and military females. The seated height, which is defined as the vertical distance from the sitting platform to the top of the head with knees and ankles forming right angles, was also reported. In addition to the studies reported by Damon,[6] Van Cott and Kinkade[25] reported data on males, taken world-wide between 1951 and 1965 with ages varying between 18 and 79, and for U. S.

females. Both civilian and military personnel were represented. The overall range for males is 28.8 to 41.4 inches (73.1 to 105.2 cm) and the overall range for females is 27 to 36.8 inches (68.6 to 93.5 cm). It is noted that there is less difference between the values for the lower limit (73.1 cm as compared to 68.6 cm) than for the upper limit (105.2 cm as compared to 93.5 cm).

In general, humans possess two legs, two arms, two hands, and 10 fingers total. These limbs cannot function independently, but must work in a coordinated manner. Typically, human's legs allow for great mobility, but also play an important role in lifting heavy loads. The range for the arm length of the typical adult, as reported by Nof and Fisher,[21] is 75.4 to 94.7 cm (29.7 to 37.3 inches).

Illustrated in Figure 1 is the dimensions proposed by Barnes[3] for the normal and maximum reach envelopes in the horizontal work platform. As shown, the maximum work area should not extend forward beyond 50.8 cm (20 inches) from the table edge and beyond 75 cm (29.5 inches) from the center to each side of the person.

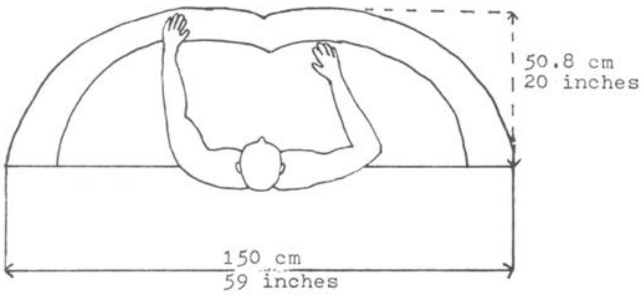

Figure 1: Maximum Reach Envelop

Anthropometric data on other types of arm reaches have been reported by Van Cott and Kinkade.[25] Arm reach was defined as the horizontal distance from the posterior surface of the right shoulder to the tip of the extended middle finger. The worker stands straight with heels, buttocks, and shoulders attached to the wall and with the right arm and hand extended forward horizontally to their maximum length. The overall range for males is 30 to 39.6 inches (76.2 to 100.6 cm) and 27.9 to 34.9 inches (70.9 to 88.6 cm) for females. Kennedy and Filler (cited in Van Cott and Kinkade)[25] reported forward reach standing values (with both hands) for males. Forward reach standing is defined as the distance from the chest to the edge of the hands with hands clenched around a tube of 1.5 inches (3.8 cm) in diameter. The measurements are taken while the subjects are standing straight and reaching forward, horizontal to the floor. The range reported is 17.5 to 25.25 inches (44.4 to 64.1 cm). Kennedy (cited in[25]) compiled anthropometric data for functional arm reaches of 20 male U. S. Air Force personnel. The subjects, while seated, reached horizontally until their arms were fully extended and this maximum distance was recorded. Reaching forward (zero degree from center) with the arm 20 inches (50.8 cm) above seat reference which is equivalent to the arm being at a 900 angle to the body while the minimum reach was 25 inches (63.5 cm). With the arm 15 inches (38.1 cm) above the seat reference, which is equivalent to a table top when seated with the minimum reach was 24.25 inches (61.6 cm). Kennedy (cited in[25]) also reported seated grasping reaches to the right side (90 degrees from center). For reaches 20 inches (50.8 cm) above seat reference, the minimum value reported was 31.75 inches (80.6 cm) and 30.25 inches (76.8 cm) was reported as the minimum value at 15 inches (38.1 cm) above seat reference. According to Nof and Fisher,[21] the maximum arm load for humans is less than 30 kg (66.1 pounds) and changes in accordance to the type of movement and direction of the load. The Materials Handling Research Unit[15] published anthropometric data on the range of weight which can be lifted by males age 40 and above. It was reported that one-handed lifts while standing ranged from 9 to 30 kg (19.8 to 66.1 pounds) and while sitting ranged from 8 to 35 kg (17.6 to 77.2 pounds). Two-handed lifts while standing were reported between 8 and 50 kg (17.6 to 110.2 pounds) and while sitting between 10 and 45 kg (22 and 99.2 pounds). It was also reported that pushing forward with one hand while standing resulted in values between 6 and 30 kg (13.2 and 61.6 pounds) and values between 10 and 50 kg (22 and 110.2 pounds) were reported for the same condition with two hands.

The human wrist has limited range of motion. According to Nof and Fisher[21] the human wrist has three degrees of freedom with roll of 1800, pitch of 1800, and yaw of 900 degrees Roll refers to the ability to turn about the horizontal axis, pitch refers to the ability to change angles with respect to the arm, and yaw refers to the ability to turn about the vertical axis. The end effectors of the human consists of two hands with five fingers on each hand. The human hands and fingers are extremely dexterous and as such are multipurpose manipulators. The typical dimensions of the hand, as reported by Nof and Fisher,[21] are 16.3 to 20.8 cm (6.4 to 8.2 inches) for length, 6.8 to 9.7 cm (2.7 to 3.8 inches) for breadth at the thumb, and 2.0 to 3.3 cm (O.8 to 1.3 inches), for depth at the metacarpal. They also noted that the fingers have a three pitch revolt and one yaw revolt joints.

Besides physical dimensions, hand strength is an important characteristic. Hand strength was measured by having the subject squeeze a hand dynamometer and recording the maximum value. Damon[6] reported range values for males between the ages of 18 and 25. For the right hand, a range of 90 to 203 pounds (40.8 to 92.1 kg) and for the left hand a range of 65 to 190 pounds (29.5 to 86.2 kg) were reported. Also reported were average values of 134 pounds (60.8 kg) for the right hand and 124 pounds (56 kg) for the left hand. Average hand dynamometer values of 64 pounds (29 kg) for the right hand and 59 pounds (26.8 kg) for the left hand were reported for males age 81.When the data is compared on the basis of age, it can be easily seen that the older males' values were less than one-half of the young males' values. Hand dynamometer values for women age 18 to 40 have also been reported by Damon.[6] The range values for the right hand are 59 to 172 pounds (26.8 to 78.0 kg) and 56 to 168 pounds (25.4 to 76.2 kg) are the values for the left hand.

Strength/Power: Strength usually refers to the maximal force exert able by a muscle for relatively few seconds. It is common knowledge that the greater the force exerted by an individual, the shorter the duration at which it can be maintained. This is illustrated by the fact that a maximal force (100 of strength) can only be maintained for a few seconds, whereas 15 to 20 of maximal strength can be maintained over many hours without fatigue. In like vein, Nof, Knight, and Salvandy[20] estimated the duration at which certain powers could be maintained; power referring to ratio of the amount of work done to the time required. They have stated that 2 hp can be maintained for 10 seconds, 0.5 hp for 120 seconds, and 0.2 hp for continuous work over a day.

Aside from genetic endowment (or natural ability), other factors affect strength. Two of the most important factors are sex and age. According to Van Cott and Kinkade.[25] Working capacity (amount of extremal physical work that can be done) of women is twothirds to four-fifths that of men. Likewise, as one gets older maximum strength tends to decrease unless the person stops the progressive decline in strength through training.

Reliability: According to Morgan, Chapanis, Cook, and Lund,[18] when used with respect to measurements of human performance reliability refers to the "consistency or repeatability of measurements." In general, consistency tends to be rather low for humans and can easily be affected by psychological or physical fatigue, boredom, and distractions. Although repeatability may improve with practice and feedback, some have suggested that external monitoring of performance may be necessary[20] as there is generally a high variability in quality and quantity of work output. Overload/Under load Performance: Overload conditions refer to those situations in which the capabilities of the human cannot meet the requirements of the system. An overload can occur when more stimuli in the system must be responded to than the person can attend and/or respond. Another way in which an overload can occur is when more physical capacity (i.e. strength) is required than can be provided. In this situation, the quality and quantity of work output will decline since the human is unable to adequately respond to the environment and since fatigue will occur rapidly. In an under load situation, quality of work output may decline as boredom and dissatisfaction result.

Reaction Time: Is defined by Woodson and Conover,[26] as the time interval elapsing between the beginning of the signal (stimulus) and the completion of the operator's response. Thus, it includes the time required by the worker to sense the signal (sensing time), in addition to the required time to decide what response to make (decision time), plus the required response time. Lags exist in all systems, but the degree of variation in reaction time is affected by specific factors such as the sense used, complexity of the signal, and signal rate, as well as by the individuals involved. Although reaction times vary, the difference between the senses is probably insignificant. The reaction time for combined. Simultaneous signals, however, is less than for the individual signal with the shortest reaction time (Woodson and Conover). As previously stated, lags exist in all systems. Grand jean[11] has even estimated average reaction time to be between 0.15 and 0.2 seconds. It has also been suggested that given the appropriate conditions, practice may reduce human time lags.[26]

Central Processes

Computation: Humans use heuristic methods to solve problems and tend to be very slow on the order of 5 bits per second. Reasons why humans are poor numerical computers has to do with the fact that humans have a limited ability to accept information (estimated at 10 to 20 bits per second) and because humans have a very limited response selection/ execution of about 1 per second (Nof, et al.). Besides being slow, humans are also subject to error and thus are not very accurate. In addition to training, experience, and stress, the meaning and connotations of signals also affect performance. Additionally. Humans are very difficult to retrain. Although slow and not very accurate humans, unlike machines, can evaluate the reliability of the information presented, can detect errors, and can correct errors (but only at the cost of redundancy).

Memory: Memory has been defined as the process of storing a select portion of the incoming information into the brain after it has been processed.[11] The process by which this selection is accomplished is unknown, but it is known that humans possess two kinds of memory: short-term memory and long-term memory. Short-term memory is limited to approximately 7 items of information and contains the recollection of events which occurred in the recent past. With short-term memory, recall tends to be poor after about 12 seconds, and after 20 seconds the information has usually disappeared.[23]

On the other hand, long-term memory has an overall storage capacity estimated somewhere between 100 million and 1 million billion bits.[10] In addition, long-term memory contains skills acquired by experience over a long period of time and is resistant to directed forgetting. Although the long-term memory access and retrieval process tends to be slow with the amount of information capable of entering permanent storage estimated at about 0.7 bits per second (once stored, information can be assessed in multiple ways). Human memory is best suited for storage of principles and strategies, and is capable of recalling generalized patterns of past experience to solve current problems.[18]

Reasoning: Humans are characterized with having excellent inductive reasoning, but poor deductive reasoning abilities. Inductive logic is characterized by reasoning from the specific to the general, where premises are determined on the basis of a few particular facts or statements. In contrast, deductive logic is characterized by reasoning from the general to the specific, where inferences are made from formal premises.

Intelligence: Intelligence refers to the ability of humans to utilize abstract concepts effectively, grasp relationships, learn quickly, and adapt to novel situations. Two important aspects of intelligence is learning and adaptation. Humans can not only receive and process information, but can change their behavior in response to that information. Likewise, humans can utilize past experiences to modify internal problem solving heuristics in response to the environment and what is learned. In addition, humans can learn by trial and error, by practice, and by transfer of previous training. Due to this, humans do not require extensive preprogramming and are capable of modifying their own programs through the learning process. Humans are also adaptive systems in that they can react to novel situations by relying on past experiences, can counteract degradation in performance brought about by a change in the environment, can anticipate problems, and can use judgement in unpredictable situations. Humans respond well to their environment, not only because they have an infinite repertoire of reactions to situations, but also because they can selectively recall relevant facts and methods to solve problems. In addition, when past experiences are not applicable to a new situation, humans are able to improvise.

Decision Making: Whereas machines require complete and reliable information to make decisions, humans do not. Humans are also unique in that they can base decisions on the synthesis of many different types of inputs.

Senses

Vision: Vision is considered the primary channel for information input and it has been estimated that the eye can transmit information at a rate of 5 bits per second per nerve fiber.[18] The stimulus for the visual system is light-radiated electromagnetic energy in the visible spectrum and Gagne[9] has estimated the reaction time for successive stimuli to be on the order of 0.1 seconds. Van Cott and Kinkade[25] have published stimulus-intensity ranges for vision with the smallest detectable amount of energy equal to 10-6mL and the largest tolerable before pain or permanent damage occurs equal to 104mL. Likewise, a channel capacity for luminance was estimated at 2.3 bits. The number of relative discriminations of physical intensity (brightness) was estimated at 570 for white light and was 375 for the relative discriminations of frequency. Only three to five discriminable intensities with white light were identifiable on an absolute basis and five to six discriminable interruption rates were identified on an absolute basis when determined by the identification of frequency. In addition to being able to distinguish between different intensities and frequencies, humans are capable of distinguishing between different wavelengths. This phenomenon is referred to as color vision. Humans are capable of seeing within the 380 to 780 nm frequency range where 380nm is perceived as the color violet and 780nm is perceived as the color red. Humans can distinguish on a relative basis between approximately 128 different hues at medium intensities. On an absolute basis however, humans can only identify approximately 12 or 13 colors. In addition, it has been estimated that the channel capacity for dominant wavelength is approximately 3.1 bits and 3.6 bits for colors of equal luminance. In general, the visual system is important as it is very good at pattern detection and keeps the human informed about changes in his environment. Due to the ability to see, humans can deal with variable materials, determine correct items quickly, position materials quickly, and determine the presence of defects.

Audition: The human auditory system is stimulated by amplitude and frequency variations of pressure in the surrounding media. The audible range for the human ear is between 16 and 20 000 Hz with the most sensitive range between 500 and 5 000 Hz.[12] According to Van Cott and Kinkade,[25] the channel capacity for intensity is 2.3 bits, for pitch is 2.5 bits, and for loudness plus pitch is 3.1 bits. The ear cannot transmit as much information as the eye but can transmit 0.3 bits per second per nerve fiber which is approximately equal to 8,000 bits per second.[18] As compared to vision, the reaction time for the auditory system to successive stimulate is less at approximately 0.01 seconds. Van Cott and Kinkade[25] report that the human ear can discriminate, on a relative basis, between 325 different intensities (loudness's) of 2.000 Hz tones. When discriminating on a relative basis between different frequencies, the ear is capable of discriminating between 1,800 discriminable tones between 20 and 20,000 Hz at 60 dB loudness. When judged on an absolute basis, three to five discriminable intensities of pure tones can be identified and four to five discriminable frequencies can be identified. Whereas the threshold of hearing is mainly affected by frequency, the threshold of feeling is independent of frequency. This threshold of feeling occurs at approximately 140 dB and is of importance as this is the threshold of pain. This does not mean, however, that damage to the ear begins at 140 dB as permanent hearing loss can occur at 85 dB Additionally, risk of damage to the ear is not uniform over the entire frequency spectrum, but is greatest for frequencies between 2,400 and 4,800 Hz [19]. A unique aspect of the human ear is its ability to interpret speech that has been distorted in frequency, amplitude, and phase. Also, the ear is very adept to distinguishing signals masked by noise.

Somesthesia: It refers to the body senses originating in the skin, muscles, tendons, joints, and viscera. Two of the sensations which are included under this heading are the cutaneous sensations and the kinesthetic sensations. The cutaneous sensations are the sensations from the skin and include touch, pressure, heat, cold, and pain. The kinesthetic sensations, on the other hand, are those which originate in the muscles, tendons, and joints. These sensations provide feedback to the brain regarding body position and movement. The somesthesia senses are important for such things as tactile coding and coding by location.

Environment

Vibration: Vibration is characterized by having a wave form which may be a simple or complex harmonic motion.[19] Most research on vibration however, has dealt with simple wave forms in which not only the frequency and amplitude, but also the direction of vibration, is of importance. Although much research has been conducted on vibration, most experiments have been of short duration, therefore little is known of the effects of prolonged exposure to vibration. In general, humans have a very low tolerance to vibration. The most common vibration problem is unwanted noise and the most common injury is sound-induced hearing loss. Also, vibration can result in annoyance, distraction, and interference due to the masking of other sounds. In addition, vibration can cause impairment to visual acuity which is proportional to the amplitude and is highest at frequencies between 10 and 25 Hz. Vibrations in the range of 1 to 250 Hz can produce headaches and fatigue and if the vibration persists for a reasonably long time intervals, permanent physical damage can occur. High intensity, low frequency sounds can cause the skull, other bones, and internal organs to vibrate and under extreme conditions damage may occur. Resonances may also occur at certain frequencies, such that the effects are much more noticeable. In addition, it has been pointed out that the use of vibrating hand tools can lead to arthritis, bursitis, injury to the soft tissues of the hand, and to blockage of the blood vessels.[12]

In respect to performance, McCormick[17] has indicated that vibration can impair tracking ability, and the impairment will be greatest at low frequencies. Other tasks which show a decrement to vibration include those which require steadiness or precision of muscular control. It has also been established that vibration increases the energy expended in working. Tasks which measure primarily central neural processes, such as pattern recognition and reaction time, appear to be highly resistant to the degradation effects of vibration. A difficulty in assessing the effects of vibration on humans is the fact that individual attitudes to vibration vary considerably and thus affect the resulting performance. Whereas some people may not even notice vibration, others will be considerably disturbed by it. Thus, it is difficult to accurately assess the effect of vibration on performance with the existence of this subjective variable.

Noise: Is best described as unwanted sound. One of the most important effects of noise is hearing loss. The amount of hearing loss is related to the level of noise exposure such that the greater the intensity of exposure, the greater the hearing loss. Hearing loss can be due to the loss of sensitivity of nerve cells: in the ear or may be the result of rupture of the eardrum due to a shock wave. When due to loss sensitivity of nerve cells, the loss is usually greatest in the 4,000 Hz range. Due to the susceptibility of the human ear to hearing loss, OSHA guidelines have been established which dictate the permissible noise exposures for workers over a given duration of time. The maximum allowable level for eight hours is 90 dBA and under no condition should noise reach or exceed 140 dBA.[12] Other adverse effects of noise include such things as annoyance, distraction, contribution to other disorders, and interference through masking of other sounds. In addition, noise may degrade certain types of performance. Noise deteriorates performance in vigilance tasks, complex mental tasks, visual matching tasks, tasks calling for skill and speed, tasks that require a high degree of perceptual capacity, and complex psychomotor tasks.

Temperature: As discussed by Gagne,[9] temperature is a stress which does not interfere directly with a sensory or motor mechanism, but influences the total comfort and psychological performance of an operator. Tests have shown that people are comfortable in temperatures of 70 to 800 F, even when humidity is as high as 70.[12] If the temperature rises to 800 F or above, a slight impairment in performance will be noticed and if the temperature rises to 900 F or above. A demonstrable degradation in mental and physical processes will occur.[9] The reason for deterioration of performance at temperatures above 800 F has to do with the fact that mental activity and responses slow down. If the temperature is at or below 500 F, performance will decline especially in those tasks which require fine dexterity as the fingers and hands become stiff.[26] Thus, the effect of temperature on performance appears to be negligible in the middle range.

Humidity: Although humidity has an influence on the perception of thermal comfort, Grand jean.[11] has stated that humidity within the range of 30 to 70 has little effect on comfort and tends to be perceived as comfortable by most people. If, however, the relative humidity falls below 30 there is a danger of having too dry an atmosphere which may cause persisting irritation of the nasal and bronchial passages. High humidity appears to be more serious as it can result in psychological and physiological stress in humans, especially when coupled with high temperature. People who work in high humidity environments tend to become irritable, suffer from fatigue and headaches, have a reduced ability to concentrate, and make more errors.[12] Thus, as humidity increases performance decreases under conditions of high ambient temperature.

Contaminants: According to Morgan[18] all atmospheric contaminants would become toxic if introduced into the body in amounts higher than some threshold value. What is important the concentration of the contaminant and the duration of exposure. One contaminant of considerable importance is carbon dioxide (C02) as it is released into the air as a substance of the body's metabolism. Concentrations above 5 in inhaled air should be considered dangerous as higher concentrations can lead to unconsciousness, coma, and even death.[12] Carbon dioxide (CO) is particularly hazardous as it is odorless and can therefore, not be detected by smell. It is also dangerous in that it is easily taken up by the body, but released very slowly. The major physiological effect of CO is to reduce arterial-oxygen saturation, thus reducing the availability of oxygen in the blood and tissues. Concentrations as low as 0.05 are considered dangerous. Carbon dioxide and carbon monoxide are but two chemical contaminants in a large array of possible toxic chemicals. They are the only ones discussed as they are very common and are meant to be illustrative.

Training

Training: is defined as the process by which individuals learn the knowledge, skills, and attitudes, not previously in their repertoires, which will fit them to function as human components in a system.[9] Inherent in this definition is the idea that individuals possess basic skills and experiences accumulated over time. Thus when training is required, a high degree of detail regarding job descriptions is usually not necessary. Also, due to the fact that humans are flexible they can be trained in a variety of ways. Besides the fact that new employees must be trained to learn a job, retraining of personnel is also required due to job transfers and the fact that people may forget. According to Nof,[20] training requires the use of a human teacher and individualized training is best. Alternatives to human teachers, such as computer aided instruction, are available and currently used. Regardless of the type of training system used, training is very costly. Additionally, not all persons will benefit equally from a given training system due to individual differences in such things as learning and motivation.

Social/Psychological Aspects

Social/Psychological: Aspects refers to those factors, which are non-physical in nature, that affect human performance in a system. The term non-physical refers to those factors which originate from such things as ones values, emotions, and needs. Such factors as boredom, motivation, fatigue, anxiety, satisfaction, temperament, and pride in work all influence performance. Boredom, motivation, fatigue, and anxiety will be elaborated.

Boredom: Boredom is the condition which results in the human when the task performed is void of any stimulation. This usually occurs with simple tasks that are prolonged and repetitive, yet does not allow the operator to think about other things entirely. Another type of task which generally causes a great deal of boredom is prolonged, monotonous supervisory work which calls for continuous vigilance. In addition to certain types of jobs, certain personal factors are also involved. For instance, night workers, people with low motivation, and people in a state of fatigue tend to have a greater liability for boredom. People with a high level of education, knowledge, and ability, as well as people who are eager for a demanding job, tend to be more susceptible to boredom.

Motivation: An important factor when the system output is considerably affected by operator performance is motivation, which is thought of as the willingness to do one's best. One way to improve motivation, and thus performance, is to provide knowledge about good performance to the operator. Feedback will aid not only in acting as an incentive for improved performance, but also as an aid in learning the job.

Fatigue: Whether physical or psychological, fatigue has the principle effect of reducing motivation and thus degrading performance. With fatigue, as with boredom, the person's attention wanders increasing the likelihood of mistakes and accidents. When fatigued, people become more careless and take chances they would not normally take. In addition to the same conditions which contribute to boredom, prolonged working in cramped, unchangeable positions result in fatigue.

Anxiety: can also depredate performance by reducing motivation and thus impairing human performance. People may become anxious when they feel that their life or performance depends on automatic devices. People also tend to become anxious under conditions in which they are not adequately informed about what is going on in the system. Humans have the desire to know as much as possible about the information pertinent to their job. Another condition which may result in anxiety is when humans distrust or dislike their fellow workers.

Individual Differences

As reported by Nof,[20] human variation within the range of 100 to 150 can be expected. People vary so greatly because they not only have different abilities, but are also affected differently by environmental stimuli. Besides the fact that there is a great deal of variation between people, it is also true that people vary from situation to situation. Due to this wide variation among people and within an individual, performance on a given task will vary greatly.

In conclusion, it is obvious that there are certain areas in which humans excel and others in which they tend to be inferior. As pointed out, humans differ in physical characteristics, such as body dimensions and strengths, in central processing capabilities, such as computational ability and ability to learn, in sensitivity of their senses, response and degree to which they are affected by the environment~ and 'degree ,to which they are affected by social and psychological factors.

In general it can be stated that when high reliability and accuracy, tolerance of extreme environmental conditions, great strength or power, high speed, repetitive performance, or deductive reasoning is required, the human will not perform very efficiently. However, the human excels in those situations in which recognition, flexibility, inductive reasoning, judgement, intelligence, adaptation, fine manipulations, and gradual degradation are required.

Robot

The term 'robot' is derived from a Czech word robotnik meaning worker or serf. According to Ayres and Miller,[2] robots are mechanical transfer and manipulator devices with some degree of generalized (multitask) capability and programmability. An industrial robot is a programmable multi jointed arms (with grippers or tool holders at the end) capable of moving a tool or work piece to a pre specified sequence of points or along a specified path within the arm's reach and transmitting precisely defined forces of torques to these points. A total of almost 5500 industrial robots were in use at the end of 1981 in U. S. According to a study made by the Robot Institute of America, as reported by Ayres & Miller,[2] the American robot populations grow from 15000 units in 1985 to about 100,000 units in 1990. Major categories and subcategories of robots can be described under the several headings as given bellow.

Configuration (or architecture)

This refers to the mechanics of the main axes and the arm structure. (Fig. 2).

Cylindrical: They have two linear and one rotational axes.
Spherical: They have two rotational and one linear axes. They are also known as polar robot.
Revolute: They utilize rotary joints to achieve horizontal and vertical motions. They are also known as jointed arms.
Cartesian: They have all linear axes. They are also known as rectangular or prismatic robots.

Additionally, the robot may be equipped with a linear lateral motion. A gantry device operates in Cartesian co-ordinates and is suspended from an overhead structure. A portal device also is suspended but employs some rotary motions.

Performance

Load capacity: This refers to the maximum load capacity in pounds (or kilograms) that the robot can carry at its wrist at the designated arm velocity. In cases when the only available configuration is for a dedicated process, such as robots that only spray paint or arc weld, a figure for load capacity is usually not applicable, especially when the required tool is an integral part of the robot.[14]

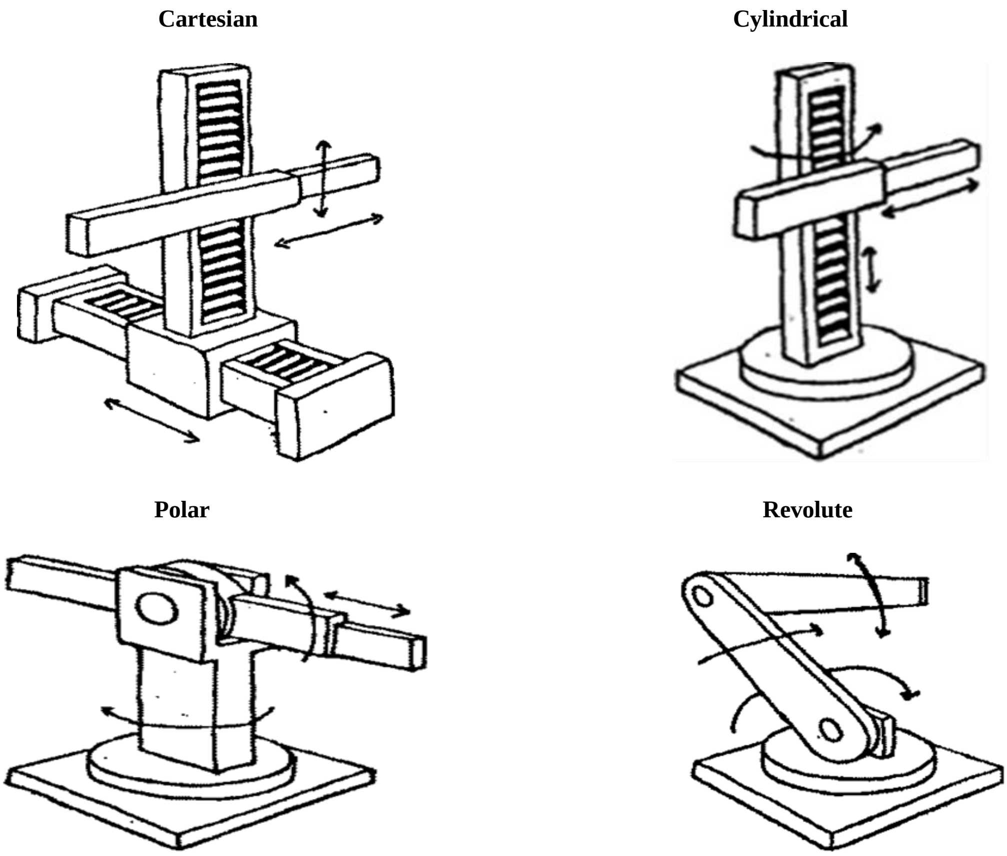

Figure 2: Robot Configuration

Horizontal reach: It indicates the maximum reach in the horizontal direction measured from the central rotational axis to the fingers or wrist. This figure has the potential of varying greatly depending on the configuration.[14] When two differently configured robots are compared for the same job, some extension figures are estimated from the manufacturer's drawings.

Vertical reach: It indicates the maximum reach in the vertical direction measured from the floor to the highest point the fingers or wrist can reach.

Sweep: This refers to the total number of degrees around the central vertical axis that the arm can reach.[14] For a Cartesian robot, a Linear X-axis excursion is usually given.

Accuracy: It relates to the robot's ability to return to a taught position within its working area. This position is usually measured at the gripper or end effector and is essentially a function of the control system's resolution, which determines the minimum distance that can be recognized by the robot through its control system. When the robot is used to manipulate a tool, accuracy is measured at a point that represents the furthest extension of the tool from the tip of the last axis.[13]

Repeatability: It relates to the robot's consistency in returning again and again to the taught point. As the majority of robots are preprogrammed with a fair degree of trial and error using a teach pendant or being manually led along the desired path with some flexibility in the positioning of the work piece, repeatability is usually more important than accuracy.[13] Clearly if a robot bas good repeatability but is not very accurate, then it may be of little use in critical applications such as arc welding or mechanical assembly where fine movements are often required.

Speed: It is defined as the robots various rotational and translational motion capabilities and velocities at which they are performed.

Drive/Actuation

It refers to the method of powering the main axes. Canoon1y used methods to drive the robot are as follows:

Hydraulic: Hydraulic cylinders and pumps areemp1oyed.
Electric: Electric motors are used.

Pneumatic: Compressed air operated cylinders are used. Combination of drives are also possible. Also, when a pneumatic drive is required only to open and close grippers (in a non-axis use) it is usually not specified.

Control

This refers to the method of positional control. Several different types of controllers are available built around standard microprocessors. The following are the three most common methods of control:

Non-servo: It is a sequential control and often uses a programmable logic controller using limit switches and/or mechanical steps for position control.

Servo, point-to-point: It is a servo control employing encoder, resolver or similar position feedback in a point-to-point (PTP) mode. With PTP capability the robot calculates the straightest path to that learned desired position from the previous position.

Servo, continuous path: It is a servo control employing encoder, resolver or similar position feedback in a continuous path mode involving velocity feedback.

Sensing and learning:

a) Internal
b) Remote (e. g. vision)
c) Contact (e.g. force, pressure)

Programmability:

a) Manual or mechanical
b) Lead-through
c) Walk through with a teach pendant.
d) Self-tutoring (by trial and error and experience)

The basic components of a robot are as follows:
Body: It is the foundation, frame or structure on which all the other components are mounted. Most industrial robots have a stationary body. However, to add additional flexibility to the robot a moving body may be designed.

Arm: It is meant to transfer the wrist and the end effector to a destined point in the work envelope. The length of the arm is an important factor in deciding the reach of the robot. The weight of the arm decides its speed of movement. The strength of the arm decides the robot load carrying capacity.

Wrist: Its use is in approaching, positioning and orienting the end effectors.

End-effector: This is the terminal component of an industrial robot. It consists of a hand-like device with two or more fingers or grippers. Specific end-effectors are used tailored to specific task requirements. Generally, the end-effectors are changeable. The main purpose of the end-effectors is to grasp the work piece, apply force to it and perform machining functions on it. According to a study made by Nof, Knight and Salvendy[20] the skill and other characteristics of a robot can be classified as follows:

1. **Physical skills and characteristics**
   a) Manipulation abilities
   b) Body dimensions
   c) Strength and power
   d) Consistency
   e) Overload/under load performance
   f) Environmental constraints
2. **Brain and control**
   a) Computational abilities
   b) Memory
   c) Intelligence
   d) Reasoning
   e) Information processing
   f) Training
   g) Sensing
   h) Inter-robot communication
   i) Reaction Speed
   j) Self-diagnosis
3. **Energy considerations**
   a) Power requirements
   b) Utilities
   c) Fatigue/down time/life expectancy

d) Energy efficiency

Current robot capabilities as reported in the survey by Fisher, Nof and Seidman[8] are as follows:

1. **Robot size (maximum dimension and robot envelope):**
   Micro (> 1meter)
   Small (1 to 2 meters)
   Medium (2 to 5 meters)
   Large (< 5 meters)
2. **Actuator type vs. repeatability:**
   0.1 to 0.5 mm repeatability is most common.
   0.002 mm is the smallest reported repeatability.
3. **Degrees of freedom:**
   5 to 6 degrees of freedom most common
   Maximum reported about 8 degrees of freedom.
4. **Lift capacity at end-effector**
   40 kg. Lifting capability is most common.
   Maximum up to 1000 kg
5. **Control mode**
   Servo, point-to-point control is most common.
6. **Sensory ability**

Position sensors are commonly used today. It is expected that force, vision, tactile and velocity sensors will became popular in near future. The unique thing about a robot is that its skills and abilities can be specified, designed and built into. The designed specifications can be chosen selectively. In contrast, human-oriented job and skill analysis has relatively much less control over the operator specifications, characteristics and abilities.

In conclusion, it can be said that robots have certain areas of strengths and certain other areas of weaknesses. Robots can perform tasks repetitively and round-the-clock. They are not affected by social psychological and physiological factors such as boredom, motivation, likes and dislikes, fatigue etc. They have good accuracy and repeatability of movements. They can be built to specifications required for the task. Robots have in general greater load capacities than humans. They have greater sweep of movement around their body. They have very good flexibility for doing different tasks and transfer of training and experience from one robot to another is easy. A robot can be programmed off-line and once programmed, re-programming is not necessary unless the task changes. Robot's memory is extendable. They are highly resistant to adverse environment. Robots can be provided with multichannel monitoring and parallel processing capabilities. Robots usually do not have individual differences unless specifically designed to have differences.

On the other hand, robots do not have the capability to learn from experience, to adapt itself to changing conditions and modify its responses. Robots are not yet intelligent or creative. Robot's senses are not yet highly developed. They cannot improvise when a response to a given situation is not present in its repertoire. They cannot make judgement to take decisions. They need extensive pre-programming and an extensive data base before performing a task. Robots cannot modify their own programs. Once over loaded, there is a catastrophic failure rather than a slow degradation of performance.

Table 1: Provides summary information on robot Characteristics.

Task Analysis

Task analysis is defined by Dunn and Rachel[7] as the Identification of the tasks and of the skills, knowledge, abilities and responsibilities that are required for successful performance. Task analysis is an approach to determine what to do in a task and uses information such as time, motions, vision, and other sensor requirements.

Task analysis has three major steps as follows:

1. Identification of the task
2. Work performed (what, why, and how?)
3. Performance requirements

The third step of task analysis requires that the analyst be more than an observer. Lot of judgement is required here. The analyst makes a detailed interpretation of traits required for successful performance of the job. The analyst reviews each task and suggests attributes the worker or robot must have. Analysis and interpretation permit a decision not only on the presence or absence of the factor, but also on the degree to which it is present.[4] Task analysis involves breaking down the task into its elements which are specified with their performance time and requirements. Task requirements could be broken down into three major sections:

1. Limbs requirements
2. Senses requirements
3. Memory and program capabilities

Described below are sane of the common manufacturing processes.

Each process has been defined and its special characteristics have been discussed.

Material Handling: It is defined as the operation of picking up heavy parts from one location or workstation and moving them to another location or workstation. Common characteristics of this operation are:

1. Handling of heavy loads
2. Substantial distance of movement
3. Positioning accuracy not very critical
4. Speed not very critical

Load and Unload: It is defined as picking up of parts, loading them into a machine and after the processing is over grabbing them and putting them down. Common characteristics of this operation are:

1. Handling of small to medium parts
2. Distance moved is usually small
3. Positioning accuracy and repeatability very important
4. Speed is usually an important consideration

Assembly: It is defined as putting together two or more parts. The combining operation could be performed in several ways as given below:

a) Mechanical assembly
b) Welding, Brazing, Soldering etc.
c) Adhesive bending

Common characteristics of the assembly operation are:

1. Accuracy and repeatability of positioning and movement
2. Substantial memory requirements
3. Load and distance of movement not very critical

Surface cleaning and coating: Surface cleaning involves cleaning of rust, scales, chips, dirt, oil, grease etc. from the surface of the work piece. Coating on the other hand involves covering the work piece surface with a chemical compound to protect it from the adverse elements or important some desirable properties to the work piece surface. Surface cleaning includes operations like:

a) Deburring
b) Polishing
c) Cleaning

Surface coating includes operations like:

a) Spray painting
b) Dip painting
c) Electrostatic painting
d) E1ectrocoating

Common characteristics of these operations are:

1. Minimum work handling requirements
2. Minimum distance of movement
3. Positioning and sensing ability very critical
4. Substantially large memory requirements

Following is a discussion on the various task elements involved in the manufacturing processes described before. Most of the task element definitions are from Maynard.[16]

Reach: It is the basic element employed when the predominant purpose is to move the hand or finger to a destination or general location. The time for reach depends on the following factors:

1. The conditions under which the notion is performed
2. The length of the motion
3. The presence or absence of acceleration and/or deceleration in the notion

Move: It is the basic element employed when the predominant purpose is to transport an object to a destination. The time for move varies depending on the following:

1. The conditions present
2. The distance moved
3. Amount of weight carried
4. The presence or absence of acceleration and/or deceleration in the motion

Grasp: It is defined as the basic element employed when the predominant purpose is to secure sufficient control of one or more objects with the fingers or the hand to permit the performance of the next required basic element. Grasp time varies depending on the following:

1. Object size
2. Search and selection required/not required
3. Presence or absence of interference with grasp

Grasp is again subdivided into the following subcategories:

1. Pickup grasp
2. Re-grasp
3. Transfer grasp

Pickup grasp and transfer grasp involves comparatively simpler motion elements compared to re-grasp.

Position: It is defined as the basic element employed to align, orient, and engage an object with another object where the motions used are so minor that they do not justify classification as other basic elements. The time for position depends on the following factors:

1. Symmetry
2. Class of fit:
   a) Pressure required
   b) Precision of Placement
3. Ease of Handling

This is an involved task element and requires visual, cutaneous and kinesthetic sensing.

Release load: It is the basic element employed to relinquish control of an object by the fingers or the hand. There are two basic types of release as follows:

1. Opening of the fingers
2. Contact release

Select: It is the choice of one object from among several. In many cases it is difficult if not impossible to determine where the boundaries lie between search and select. For this reason it is often the practice to combine them, referring to both as 'select'.[3]

The manufacturing processes described before are analyzed, into their basic task elements. Each task element is further broken down into the factors involved in performing the tasks. Desired robot characteristics for performing the tasks are specified, along with their respective levels. Human traits needed to perform the same tasks are also provided.

A survey of currently available robots was made to establish the relationships between the intended application of the robot and its characteristics.

The highlights of the survey are as follows:

1. Revolute configuration is more common among painting, welding, inspecting and assembly robots.
2. Cylindrical configuration is more common in all types of material handling process robots.
3. Inspection, pick-and-p1ace and assembly processes require the least load capacities, whereas, material handling and loading- unloading requires the most.
4. Electrical drive seems to be the most popular among all types of robots.
5. Assembly, welding and painting processes require most memory capacity.
6. Inspection, assembly and pick-and-place activities require most in terms of repeatability.
7. Reach requirements for inspection, assembly and pick-and-p1ace are lower than welding, painting and material handling in general.

The above conclusions were based on the average statistics only. However, look at the reported ranges of robot characteristics show a very high degree of overlap between different manufacturing processes. For example, a robot intended for material handling should ideally have high degree of load capacity and low memory and repeatability. But in practice, the robot manufacturers in a bid to capture a larger share of the market, builds a general purpose robot. Hence we have material handling robots having load capacity as low as 2 Ibs, The general result is that of overdesign, higher prices and ultimate- underutilization of the industrial robot. It is expected that awareness of the intended task requirements will lead to designing of robots which- are task oriented robots which are meant for specific manufacturing processes. This will lead to lower prices and better utilization of the robots. I t is however realized that there will always be a market, however small, for a general purpose robot capable of performing an array of tasks. But then the user of such a robot should be willing to pay the extra cost necessary.

Task Allocation

Task allocation in the present context can be defined as the process of determining whether humans should do a job or robots. This involves the determination of the relative abilities and limitations of robot-oriented and human-oriented job performance.

As the future need for increasing productivity and decreasing cost grows, it will became increasingly important to utilize all the human and physical resources optimally. This will necessitate the need for a new look into the allocation of tasks between humans and robots on a continuous basis.

Advantages of robots over humans have already become clear in many applications. Some of the more common uses and their percentage distribution in the US are reported by Ayres and Miller[2] as follows:

Application	Estimated Percentage of US Robot Within
Welding	34%
Machine loading/unloading	20%
Foundry	19%
Painting	12%
Assembly	2%
Other applications	13%

Guidelines

1. Analyze the task and establish the task requirements with regards to the following: physical efforts, mental efforts, skill, training, knowledge, and environment.
2. Match the task requirements with human characteristics and establish the human traits required to do the task.
3. Match the task requirements with robot characteristics available and specify the right combination of characteristics for a robot to do the task.
4. Perform an engineering economic analysis to decide whether human should perform the task or robot or a combination of both from an economic standpoint.

Conclusion

The objective of this paper is to provide a guide for assisting in the allocation of tasks between humans and robots. To achieve this objective, the capabilities and the limitations of humans and robots were presented. The information presented should not be regarded as conclusive and final. Task allocation was described and guidelines were offered. Several common manufacturing activities were analyzed into their basic operational elements where the robot and human capabilities required to perform each operation was noted. This type of breakdown could serve as a decision making aid for task allocation.

It is important to note that the steps outlined for task allocation are not comprehensive. After a decision is made regarding whether a human or robot is best suited to perform a given task, economic considerations must be addressed. The notion that human characteristics will not change considerably in the future, whereas robot capabilities will undoubtable improve as technology advances, is important to keep in mind. Two major limitations of present-day robots, which technology must address, are the limited sensing capabilities and inability to handle unstructured situations.

Ideally, as robots become more integral part of the factory environment, the conflict which presently exists between humans and robots will disappear and instead humans and robots will assume complimentary roles.

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