Chapter 2
Need and Functionality Analysis

Generally the word "smart" is used synonymously with "intelligent," but in reality the dictionary definition of "smartness" is "marked by often sharp forceful activity or vigorous strength," that is, it is active. Thus, a "smartphone" can only wake you up with an alarm, but in reality it is smart only if it can "slap" you if you don't wake up! Fig. 2.1 shows the hierarchy of systems ranging from "passive" to "intelligent".

In fact there is a fundamental divide between being intelligent and being smart. Your computer or your cell phone is intelligent. You do what it tells you to do. Think about this for a minute. Your computer is your "boss". You wake up and look to it for instructions, (email, calendar, etc.) you do what it says and then you report back to it. If that is not a definition of a "boss," we don't know what is? On the other hand, your car is like your valet or butler: you tell it what to do and it actually carries out the actions. These are "actuators" that perform actions (typically mechanical) based on our command. It is the latter category that we need to focus on.

The capabilities of your car came from the assembly or configuration of its parts, just like the first "valves" were made by assembling parts. Today, most actuators (think solenoids, electric motors, etc.) are in this stage of development. Over time, the valves gave way to transistors (where the configuration is microscopic) and finally to very large scale integrated circuits (VLSI) where the functionality is from its "microscopic" configuration and no further assembly is required. We are gradually heading to this stage in actuators too and the challenges are immense due to the need for motion. Just as information technology is based on the ability to store, manipulate and retrieve information (bits), actuator technology is based on the ability to store, retrieve and manipulate shapes or geometry. For cars, and electric motors, this ability to change geometry is based on the assembly of parts. Shape memory alloys (SMA) have this ability because of their "microstructure." They are the equivalent of transistors.

In order to have the ability to store shapes and retrieve them on demand, we need to supply two things: Energy to transform the shape and a means for transmitting a "signal" to initiate the shape change. For a typical SMA, the energy is in the form

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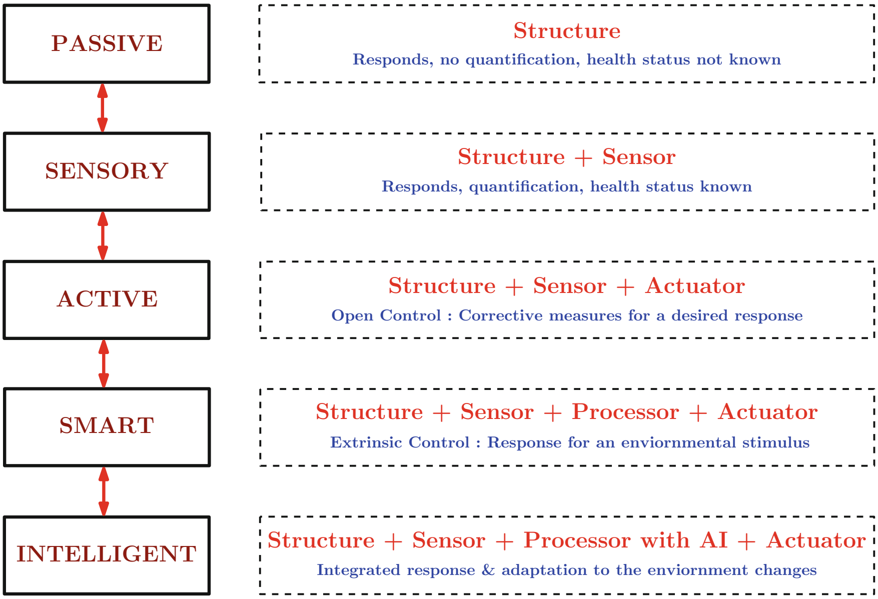

Fig. 2.1 Smartness in systems—a hierarchy

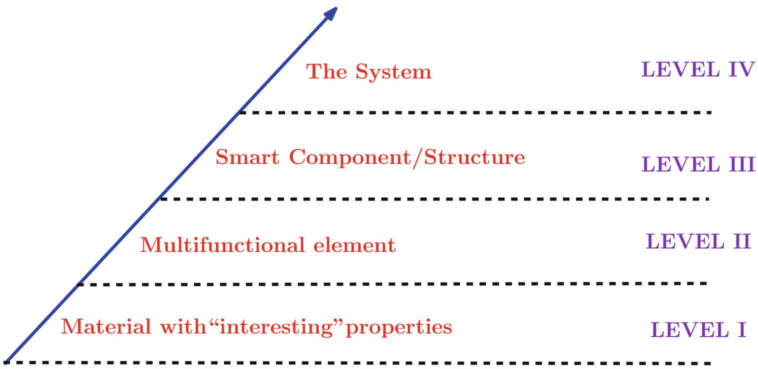

Fig. 2.2 Smart system: an integrated use of components/structures, actuators, sensors and control systems that can reversibly respond to changes in external conditions

of heat and the signal is a temperature signal. The core idea here is to find or create materials with "interesting" properties and create such systems (see Fig. 2.2). The question is how best to design components that can exploit this ability? We turn to this in the next section.

2.1 The System Design Process

One of the key activities that distinguishes humans from other animals is our ability to *design*, that is, create or synthesize something that we can use that wasn't there before. This activity of designing is something that we take so much for granted that we automatically do it without paying much attention.

So what is this activity called designing and how do we do it? *Design is the act of identifying societal needs (who is the end user? and what do they need?) and constraints; quantifying them and using a combination of scientific principles and experience to synthesize products and processes to satisfy the needs.* This combination of products or devices and processes that they can undergo is called a "system." Thus we have the electric grid system, the sanitation system, the transport system, the computer network system, etc.

The above quote shows the essential difference between a scientist and an engineer: a scientist typically creates "explanations". An engineer creates products and processes. In other words, when you are explaining how nature works, you are undertaking a scientific activity. On the other hand, when you are building a product or a process, you are undertaking an engineering activity.

Thus all designs start with the the idea of "I/we want...," "I/we need...," or "wouldn't it be nice if we could..." and ends with a specific product (cell phone) or process (wireless transmission). For a design example, if one looks at a cell phone, it is a product that allows to communicate and record information (need) in a portable way (constraint). However, the task of designing is not a simple linear process starting from a need and ending in a product. It is fundamentally *iterative*: We don't quite know what we want when we start but as we begin building we discover things and improve our design. There are thus three major activities that occur in a cycle (see Fig. 2.3) involved in designing things:

1. identification of needs and constraints,
2. embodiment or synthesis of product or process, and
3. evaluation of the product or process to see if it meets the need or constraints.

Typically, if you are a novice designer, (remember your high school project), you will do this iterative process at a subconscious level, without thinking deeply about it. In particular, you probably built and rebuilt your product until it worked (probably many times). However, this is not a sensible way to carry out large projects. Imagine building a bridge this way: You "eye ball" the river and begin building; at the end, if your bridge doesn't reach the other end, or if the first truck that goes across it plunges into the river, you say "oops ... let us rebuild it," and start over. This would not be a viable process. Similarly, if you are building a rocket going to the moon, you don't say, "oops ... missed again," and then rebuild the rocket. The lesson to learn from these admittedly extreme examples is that *avoid a simple trial and error approach when designing.*

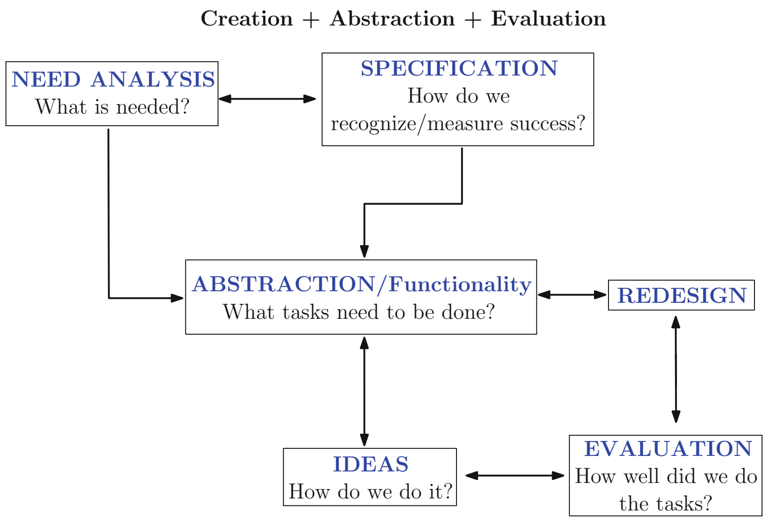

Fig. 2.3 Design methodology involves creation, abstraction and evaluation: structure and guidelines

A much better way to design something is to follow a systematic design process. There are many ways to organize this process and one such way is shown in the Fig. 2.3. Note the number of cycles or iterative loops in the process. The essential process is described in the subsection.

2.1.1 Design Methodology: Structure and Guidelines

The list below (see Fig. 2.3) is a very abbreviated/bowlderized version of Nam Suh's *Axiomatic Systems Design Approach* [1].

1. Know your clients, not only users but all those who are affected by your design.
2. Develop a need statement. A precise, abstract, qualitative high level statement that incorporates the principal need(s) and the principal constraint(s).
3. Develop a function hierarchy or function structure. Each function should be an action that has to be performed on an object producing a measurable outcome. The hierarchy is arranged in a tree so that asking "why should this function be performed?" leads up the hierarchy into the root of the tree. Asking "how this function is to be performed?" leads down the hierarchy into the "leaves."
4. Using the outcomes of the function hierarchy, develop specifications that will be used to measure the degree of success of the design. This is typically done using a "Quality Function Deployment Technique" or "house of quality" [2].

5. Develop at least three embodiments that can be used to satisfy the functions. The guidelines for developing embodiments are given below:

   a. Separate functions. Don't have more than one optimization criteria for a single component.
   b. Provide short and direct paths. Don't make complicated conduits; Don't make too many transformations of energy etc.
   c. Exploit symmetry. This is the idea of "balance" and "harmony" in art and design.
   d. Avoid sharp gradients. Don't make abrupt changes in properties or geometry and try not to connect dissimilar components together.
   e. Minimize interfaces. Pay close attention to transitions or connections (most designs fail at the connections)
   f. Do not over constrain.
   g. Minimize information content. More parts, more items to specify the less elegant is the design

6. For each function, evaluate how well it meets the need and specifications.

Each of the above items requires an extensive discussion which is outside the scope of this book. In many cases, the specifications will change as we design (since we will know more about the product than when we started, and people will gradually realize what they actually wanted) hence this is an iterative process. Most design books suggest that about 50–80 % of the cost of the product will be set at the time when we are designing. In other words, it is well worth your time and effort to go through many "paper" iterations before actually building the product. This is a hard thing to do, since it appears that we have made no progress, but in reality, it will considerably shorten the total design time since it will eliminate many costly mistakes or misunderstandings

It is clear that if we could *predict* the way your product or process is going to behave *before* you build it then you wouldn't have to actually build the product to see if it works. You could save time, money, and even the lives of many people, if you could *mathematically* simulate the process or product under a variety of conditions and test its performance virtually. Use science and mathematics.

One can predict the behavior and evaluate its performance, only if we have scientific (reproducible) explanations for its behavior and mathematical quantification of its performance. For example, if one wants to predict whether a bridge or a building is strong, one needs a scientific explanation of how bridges or buildings fail and a quantification of how much load this particular bridge or building has to withstand. Hence the essence of engineering is *quantitative decision making*, that is, measure or calculate something and then make decisions on whether it is sufficient or not.

This point is so important that we will restate it.

> The purpose of all engineering calculations is to make decisions in other words, for EVALUATING options. Thus, engineering is the art of quantitative decision making,

In your statics and dynamics class, when you solve truss problems and were asked to find forces in a truss, why did you need to do that calculation? You need to do it in order to decide whether the truss is safe (i.e., whether it will collapse or cease to function) or not. In the same manner, EVERY calculation that we make in engineering has a decision attached to it. This is one of the reasons that engineers are in such demand: they have been taught the process of quantitative decision making that is essential for so many disciplines. The purpose of the course on mechanics of materials is to help you master this capability of decision making in structural engineering.

2.2 The Five Major Subsystems

In the previous section we introduced the notion of the design of a "system" to satisfy a societal need. In order to gain a better understanding of such systems, let us consider an example system such as a car (which is itself a part of a transport system).

Can you think of what societal need a car satisfies? it is a system to transport by land, a small group of individuals and objects (luggage) safely and at a reasonable speed between any two chosen locations. This is what a car *does*. The above description of what a car does is called a *need statement*. Notice how it is an abstract statement (i.e. it does not directly reference what a car looks like (its embodiment) or even how it does what it does. It describes what happens to the user when they use a car, somewhat like a "before" and "after" statement.

Another example that might give you some insight into a need statement is that for a pen. What societal need does a pen satisfy? Before you read further, just pause and write down what you think is an answer. As a hint, imagine why you wanted to use a pen and what happens when you finish using a pen. A pen is a device that records information in a visually retrievable form on a two dimensional surface. You might have had something like "a pen writes on paper." What a need statement does is asks, "give me a physics description of "write" and "paper." In the need statement here, we have converted "write" into "record information in a visually retrievable form" and "paper" as "two dimensional surface." You might quibble with this but that is quite acceptable; your definition may be at variance with ours.

The point about a need statement is that it allows for other possible solutions than just the one that we are currently utilizing. For example, we now have electronic versions of this, namely the iPad® and other tablet computers that can do the same thing. Thus a pen, a pencil, and a tablet PC are all different "embodiments" that satisfy the same need statement in different ways. Seen in this way, a car is a specific embodiment. A scooter, a bicycle, and (if you are in India) an auto rickshaw are other embodiments that offer personal land transportation.

In spite of the different embodiments looking completely different, all embodiments share some common features from a scientific point of view. They are all systems that can transmit, convert store or dissipate some basic physical quantities.

Different embodiments differ in the extent to which they carry out this activity. Specifically, every embodiment can have the following features:

1. *Transmit and store momentum.* Systems whose primary task is to transmit momentum are called structures. If a system can also store momentum then it is said to have inertia. Classical physics tells us that we cannot convert momentum.
2. *Transmit, store and convert mass.* Systems that are primarily designed to transmit mass are called conduits pipelines, etc. Mass of one kind can be converted through chemical reactions to other kinds of mass and systems that can do this are called chemical plants or reactors.
3. *Transmit store and convert motion.* Systems that are primarily designed to transmit and convert motion are called mechanisms. By motion conversion, we mean converting rotational to translational motion, etc. springs and solenoids and SMAs are designed to "store" and convert motion.
4. *Transmit, store and convert power* (*specially mechanical and electrical*). Systems that are primarily devoted to transmit power are called power transmissions or simply "transmission." We emphasize that you cannot transmit mechanical power without simultaneously transmitting force and motion. Power conversion devices are generally referred to as "transducers." If a system converts chemical or thermal power to mechanical power it is called a "heat engine" or simply engine. If it converts electrical power it is called a "motor." Power storage devices are generally referred to as "batteries."
5. *Transmit, store and convert signals/information.* Systems that are primarily devoted to transmission, storage and conversion of signals are called information systems. If they are also used in conjunction with the other systems they are referred to as "control systems."

How does this classification come into play with a car? Some comments are in order.

1. The body of the car and its suspension are primarily involved in the transmission of forces and momentum and so they are the structural system of the car.
2. The engine and the AC system is naturally the power system or transducer in the car.
3. The fuel and electrical conduits, the heating and AC conduits and the doors and windows are the system involved with transmission of mass.
4. The sensors, speedometer, indicators, steering wheel, brake[1] and so on, form the information system in the car.

[1]You might be thinking, "wait, the brake transmits forces. If you think about it a little bit, you will realize that the brake only transmits the braking signal to the hydraulic system that actually supplies the braking force." You cannot stop the car with the force generated by your foot.

2.3 How Do We Identify Need and Functionality for SMAs

A SMA actuator is indicated when one needs motion with a large strokes and forces in a confined area and with a small footprint. SMA is like a solid-state micro scale hydraulic actuator. Due to its very inefficient energy conversion capabilities (less than 5 % conversion efficiency) it is not yet competitive with piezoelectric vibrators and motors for rapid repeatable action. However, due to its large stroke and wire-like form factor, it has its niche (which is growing rapidly).

NiTi SMA wires being very corrosion resistant and thus find suitable applications for use in harsh environments or for deployment in situations where maintenance is not easy. For example, it could be used for various applications in solar plants where heat is readily available and slow large motion is required. Since, SMAs performance can be affected by operating temperature, loading condition, loading rate, component geometry, material composition and thermomechanical history, it is essential to design a proper feedback control system if precision motion is required. However, in many applications, it is sufficient to develop a "two state" or two configuration system, that is, a simple "on-off" type mechanism such as for an emergency relief valve. In these cases, we can obtain guaranteed motion by incorporating a "slot" or a "cam" in the system so that motion of the wire is guided and the "on" and "off" positions are precisely located.

In general, the following questions need to be asked before deciding on the use of an SMA actuator:

1. *Is the motion needed primarily linear* "*back and forth*" *rather than cyclic* "*rotary*?" If it is a full rotatory motion, it might be better to use an electric motor.
2. *Is the intended motion fast or slow, i.e., what is the cycle duration*? If the frequency is in the range of 1–10 Hz then it would be reasonable to use an SMA. Above that, there might not be sufficient cooling time for the SMA to retract and complex multiplexing or cooling systems may be necessary.
3. *Is it a two state system*? SMAs perform very well in such situations where precise location is required only at the start and the end.
4. *Is it going to be used primarily for power conversion* (i.e. *as a heat engine*)? If so, then other technologies may be more competitive due to their higher efficiency. SMAs could be useful only in cases where there is limited space.
5. *What kind of heat source is available*? Electrically heated systems perform best due to the relative ease of heating, however cooling is always a problem. If direct heating is not possible, then circulating a heated fluid may be very effective (e.g., an SMA tube with internal heating/cooling fluid flow may be feasible). There have been designs where an external Nichrome wire was wrapped round the SMA to heat it by passing current to the Nichrome wire.
6. *What is the operating temperature*? *Are there temperature fluctuations*? Typical SMAs work very well between room temperature and about 150 °C. While there are high temperature SMAs they tend to have brittleness and stability issues and may be very expensive. Also ambient temperature excursions may cause either

premature or delayed actuation and hence it is better if SMAs are in enclosures that are reasonably well protected unless great precision is not needed.

7. *How many cycles should it be able to run for*? SMAs are remarkably tolerant to corrosive environments but repeated cycling causes "memory loss" (a phenomenon that is common to laptop batteries and in some sense similar to it) and eventual degradation. Thus, if a large number of thermomechanical cycles are needed, it is best to restrict strains to about 2–4 % even though it may be able to be deformed and recover to nearly 8 % strains. Commercial vendors typically suggest about 4 % strain

Once these questions are answered, the feasibility of using a SMA may be determined.

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