AN EVALUATION OF AN ELECTRICAL SYSTEM FOR A SOLAR POWERED CAR

by

Mark A. Oliva

Project and Report submitted to the Faculty of the

Virginia Polytechnic Institute and State University

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

in

Systems Engineering

APPROVED:

L. K. Harmon, Chairman

B. S. Blanchard

M. W. Cardullo

April, 1994

Blacksburg, VA

AN EVALUATION OF AN ELECTRICAL SYSTEM

FOR A SOLAR POWERED CAR

by

Mark A. Oliva

Committee Chairman: L. K. Harmon
Systems Engineering

(Abstract)

This project examines the initial system analysis and system level design for an integrated electrical system to be used in a solar powered car. The system design includes the ability to collect and store solar power, as well as manage control signals. The electrical motor for the purposes of this report is considered as part of the mechanical system of the car. The report follows the rigorous systems approach format for as adapted from Blanchard and Fabrycky's Systems Engineering and Analysis (1990). The report begins with a statement of the problem, and continues through preliminary design.

TABLE OF CONTENTS

LIST OF FIGURES iv

LIST OF TABLES v

DEFINITION OF NEED 1

PROJECT METHODOLOGY 6

SYSTEMS ENGINEERING PROCESS 8

SYSTEM ASSUMPTIONS 11

REQUIREMENTS DEFINITION 12

MAINTENANCE CONCEPT 21

FUNCTIONAL ANALYSIS 25

PRELIMINARY SYSTEM SYNTHESIS 36

REQUIREMENTS TRACEABILITY 42

REQUIREMENTS ALLOCATION 49

SYSTEM OPTIMIZATION 53

LIFE-CYCLE COST ANALYSIS 58

COST-BENEFIT ANALYSIS 61

COMPARISON TO CASE STUDY 63

REFERENCES 68

LIST OF FIGURES

Figure 1 - Scope of System..5

Figure 2 - System Life-cycle Process...........................7

Figure 3 - Synthesis Tier Process Flow.........................9

Figure 4 - Power Profile.......................................17

Figure 5 - Maintenance Concept.................................24

Figure 6 - Initial Operational Functional Flow.................26

Figure 7 - Collect Power Functional Flow.......................27

Figure 8 - Manage Power Functional Flow........................29

Figure 9 - Provide Status Functional Flow......................30

Figure 10 - Provide Power Functional Flow......................32

Figure 11 - Provide Motor Control Functional Flow..............33

Figure 12 - Maintenance Flow...................................35

Figure 13 - Solar Panel Requirements Allocation................37

Figure 14 - Control Subsystem Requirements Allocation..........40

Figure 15 - Power Subsystem Requirements Allocation............41

Figure 16 - Requirements Traceability Diagram...............43-48

Figure 17 - System Level Requirements Allocation...............50

LIST OF TABLES

Table 1 - Reliability Optimization Worksheet 55

Table 2 - Configurations for Reliability 56

Table 3 - Initial Production Cost Estimates 59

Table 4 - Life-Cycle Cost Analysis 60

DEFINITION OF NEED

The United States federal government has placed a high priority on a transition from traditional gasoline powered automobiles to vehicles which produce significantly less or no pollution. The reasons are two-fold: 1) to curb reliance on foreign petroleum resources, and 2) to help stabilize and clean the ever-worsening environment.

Although current estimates vary, most models forecast that the increase in use of motor vehicles using conventional fuels will lead to irreversible damage to the environment within the next 50 years[1]. The source of the reported damage is primarily three types of air pollution related to motor vehicles: Nitrous Oxides (NOx), Carbon Monoxide (CO), and Ethylene (C_2H_4). The makeup of "clean air" is typically (by volume) 78% Nitrogen, 21% Oxygen, and up to 0.99% of inert gases such as rare gases, Carbon Dioxide, and Hydrogen. Once an impurity reaches the levels on the order of 1 ppm it is considered a pollutant, and can measurably affect the environment. For example, a 0.5 ppm impurity of the Nitrous Oxides has negative physiological effects on the lung cells of most air-breathing animals, whereas 1 ppm of Carbon Monoxide has a measurable effect on humans.

As of this decade, Carbon Monoxide levels in many cities across the United States measure over the 1 ppm level. Currently, Carbon Monoxide is believed to account for half of all airborne pollutants, including particulate, in the world. Over 60% of this amount is directly attributable to conventional motor vehicles[8].

The hazards of air pollution are not limited to animals, though. Green vegetation, which relies primarily on Carbon Dioxide from the air, is highly sensitive to relatively minor levels of pollution. Due to the low percentage of Carbon Dioxide in pure air, about 0.03% by volume, any significant amount of pollution will greatly impact the percentage of Carbon Dioxide available. To make matters worse, green plants are slow to adapt to changes in air quality, and are forced to absorb large amounts of airborne impurities, which ultimately are passed directly into the ground to contaminate water[1].

Aside from the environmental concerns, the United States has grown increasingly dependent on foreign sources of petroleum products, primarily due to the demand for motor vehicle fuel. Many estimates claim motor vehicle demand accounts for over 50% of the domestic use of foreign petroleum products[3]. The oil crisis of the 1970s brought this issue to the forefront of the federal government. There is current legislation which mandates that by 1997, at least 10 percent of all vehicles produced for commercial sale within the United States produce no emissions into the air (in certain states)[1].

Recently, there has been a dramatic increase in the research of electrical vehicles as the most likely candidate for a production automobile with no emissions. One specific alternative being considered is a solar powered car, which uses energy collected from the sun to maintain an electrical charge in batteries which power the car. This energy is collected by photovoltaic cells, which convert the impending photons of sunlight into a voltage potential, or usable electrical power. This power is stored in secondary "rechargeable" batteries, which in turn provide the energy to a motor which moves the vehicle.

An electrical system is necessary for any solar powered vehicles, independent of the mechanical system which includes such elements as the structural support and wheels. The major domestic car manufacturers have designed many feasible mechanical systems for electric or solar powered cars, which account for the specific needs of these vehicles. For instance, complete suspension system designs, including specialized tires and bearings, have become industry de facto standards. Other mechanical system designs, such as drivetrain, brakes, and body are considered relatively stable in architecture[8].

However, there is currently no commonly accepted design for this type of electrical system in commercial vehicles in the United States. Manufacturers are placing a high priority on this effort, and more dollars are being diverted into research and development of these systems, including sponsorship of design competitions, international consortia, and special interest groups. The scope of the system is depicted in Figure 1.

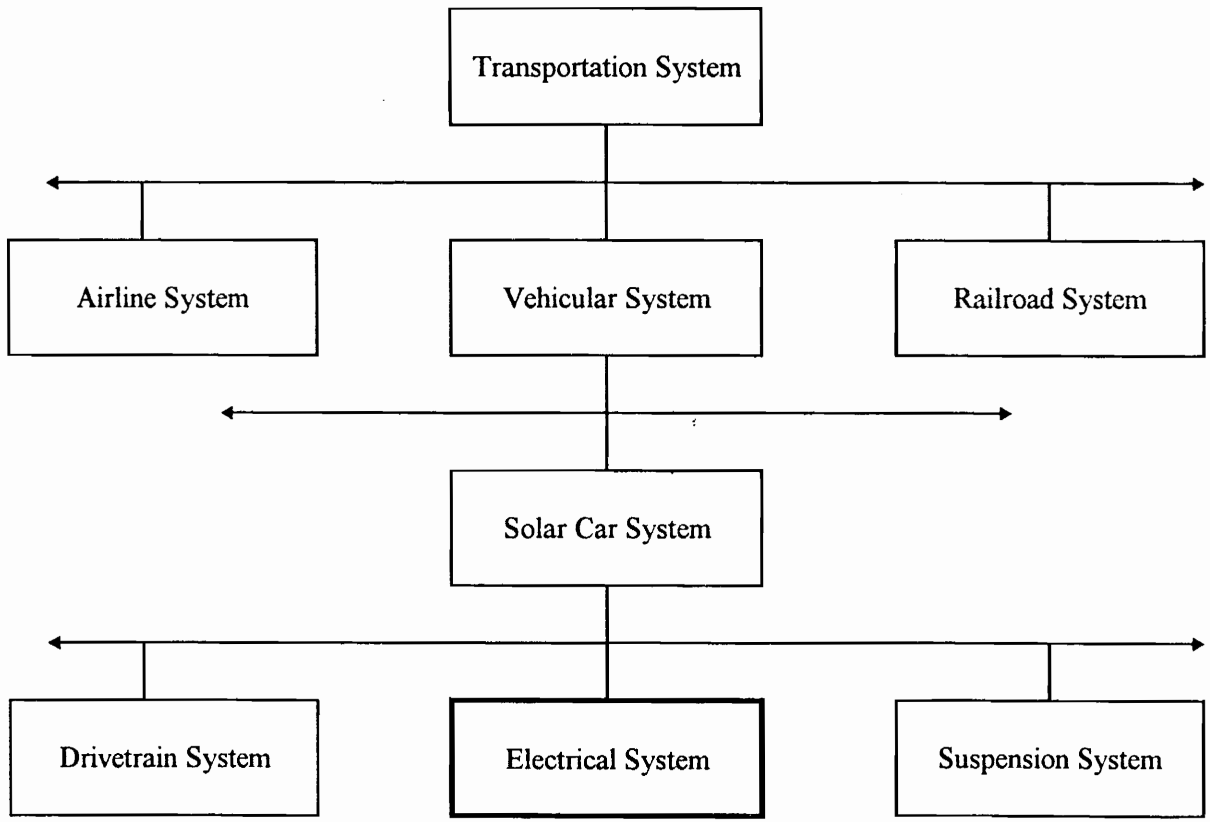


Figure 1 - Scope of System

PROJECT METHODOLOGY

The primary purpose of this project and report is to apply the Systems Engineering Approach to design an electrical system for a commercial solar powered car. As such, the electrical system will be designed based on commercial acceptance and expected demand, because manufacturers must produce these cars as a significant portion of their fleets. Thus manufacturers will seek to maximize potential profits from these products, and therefore attempt to maximize consumer appeal. This design follows an adaptation of the systems engineering process described in Blanchard and Fabrycky's Systems Engineering and Analysis (1990)[2]. More specifically, the process as outlined in Figure 2 shows an adaptation of the system life-cycle approach, described in further detail below.

The secondary purpose of this project is to compare this design to a case study design, which did not utilize the Systems Engineering Approach. Through this comparison, it is expected that certain qualitative measures may be identified as value added directly attributable to the application of the Systems Approach.

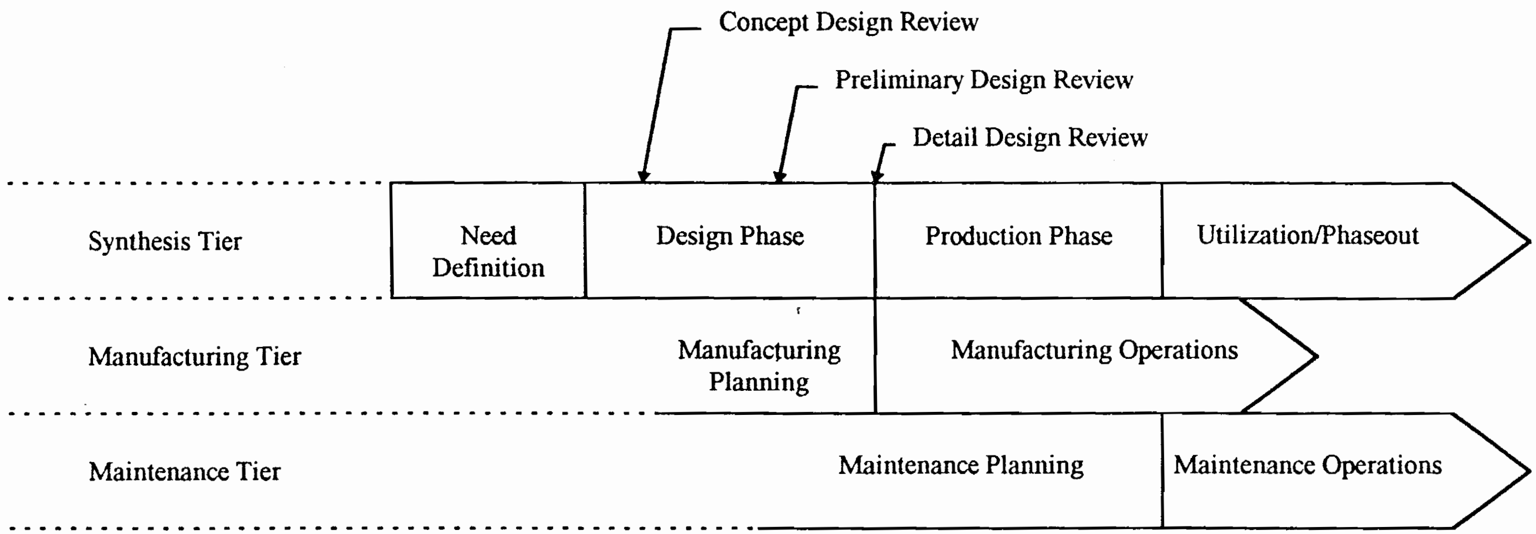


Figure 2 - System Lifecycle Process

SYSTEMS ENGINEERING PROCESS

The systems process depicted in Figure 2 focuses on a system life-cycle framework. The process evolves simultaneously, with continuous feedback to ensure an inherently efficient system. The approach consists of three tiers, where each of the concurrent processes must be considered as a whole, not separately. The scope of this project spans primarily the synthesis tier. The synthesis tier is described more completely in Figure 3. The first step in the design phase is requirements definition, wherein system level requirements are derived from the perceived needs to determine specific quantitative and qualitative criteria. Next, a functional analysis is performed on the system requirements to generate the set of derived functional requirements. These derived functional requirements are then analyzed to determine the physical assemblies which will fulfill the requirements. This synthesis of the system is followed by a requirements allocation process, which analyzes the various assemblies' requirements throughout the system for their impact on the overall system.

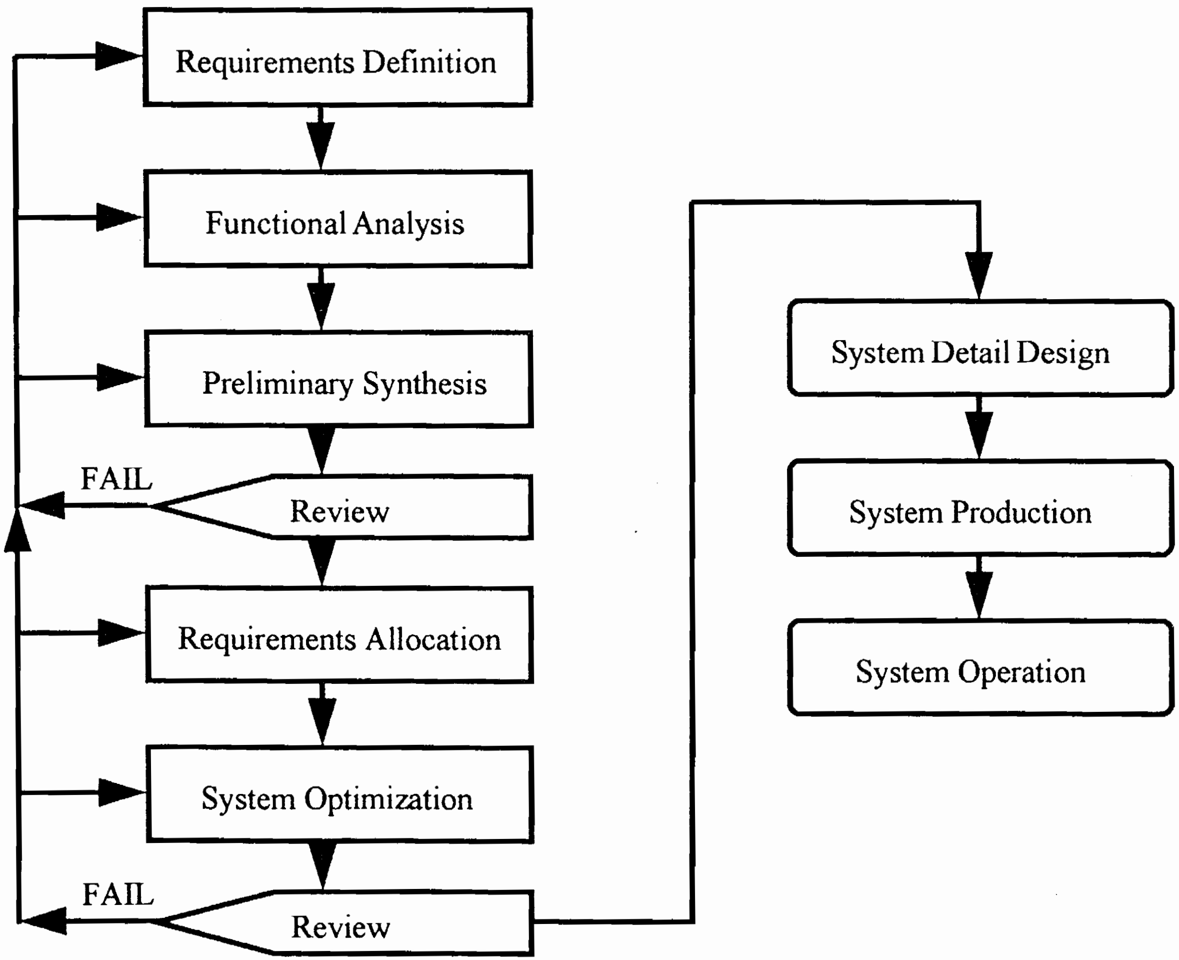


Figure 3 - Synthesis Tier Process Flow

The synthesis tier design concludes with the detailed design, which decomposes the assemblies into components, and further into the source selection process. After the design, the system is produced, distributed, operated, and finally retired. Concurrently with the initial stages of synthesis, the manufacturing tier processes begin. The design stage of manufacturing involves planning and procurement of resources necessary to produce the system. The third tier, maintenance, is also performed concurrently, from the maintenance concept, identified as input to the functional analysis, through the procurement of maintenance resources.

SYSTEM ASSUMPTIONS

This section details the assumptions made throughout this project. The mechanical system is being designed independently of the electrical system. The motor, while an electro-mechanical device, is assumed to be a part of the mechanical system which requires input from the electrical system in the form of electrical power and a control signal. The mechanical system will place few limitations on the electrical system, as it is primarily designed to meet performance, safety, and aesthetic requirements. With the exception of weight, it is assumed that there are no mechanical restrictions placed on the electrical system. The primary focus of electrical system optimization is efficient system level use of power, while maximizing reliability and minimizing life-cycle cost. Additionally, the mechanical system, which includes an integrated solar panel with a given 12 m^2 solar collection area, is optimized for aerodynamics and low rolling resistance; so, a minimum of power to the motor will propel the car[6,7].

REQUIREMENTS DEFINITION

Based on the above assumptions, numerous prototype cars have been built which confirm the feasibility of the mechanical systems specified. The main barrier to implementation of technology to the solar car system is the electrical system. Specifically, the ultimate performance of the solar car system is currently constrained by the efficiency of solar collectors and the storage density of batteries. Mechanical system technologies, including aerodynamics and low rolling resistance bearings, currently allow cost effective solutions approaching an 80% system efficiency[6]. Electrical system technologies, however, have much room for improvement. For example, the best solar collectors available currently are under 20%, and although battery efficiencies are high, their weight becomes a significant limiting factor in a solar car application[6,10,12].

The solar powered car is intended to use only power available from storage or collected from the sun while driving. While the car is parked, power may be collected from the sun and stored, or power may be obtained from standard household electrical outlets. Specifically, it is not envisioned that the driver must fuel the vehicle by introducing chemicals into the battery, nor must the driver replace batteries as a routine means of powering the vehicle. These requirements have been determined by various consumer preference studies performed by automobile manufacturers[3,5,6]. Additionally, there is a human factors requirement to provide the operator with certain status indicators, such as the amount of remaining energy, and an operator interface as similar as possible to conventional gasoline powered cars. Finally, the electrical system must be electrically self sufficient, in that any devices within the system must utilize only power generated from within the system. In addition to the above operational need, there are also performance, maintenance and reliability considerations.

The performance requirements are extracted from analyses of consumer preferences, coupled with constraints from the mechanical system[5,7,12]. Since the electrical system is intended for use in commercial vehicles, for sale within the United States. Consumer appeal is therefore a critical component to the success of the system. An efficient system which is not accepted in the marketplace will prove to be a burden to the car manufacturers. These manufacturers must, by law, produce increasingly more zero-emission cars within the next 3 years and beyond. If the solar powered cars are not viable to consumers, the manufacturers will be forced to endure an unacceptable loss of profits.

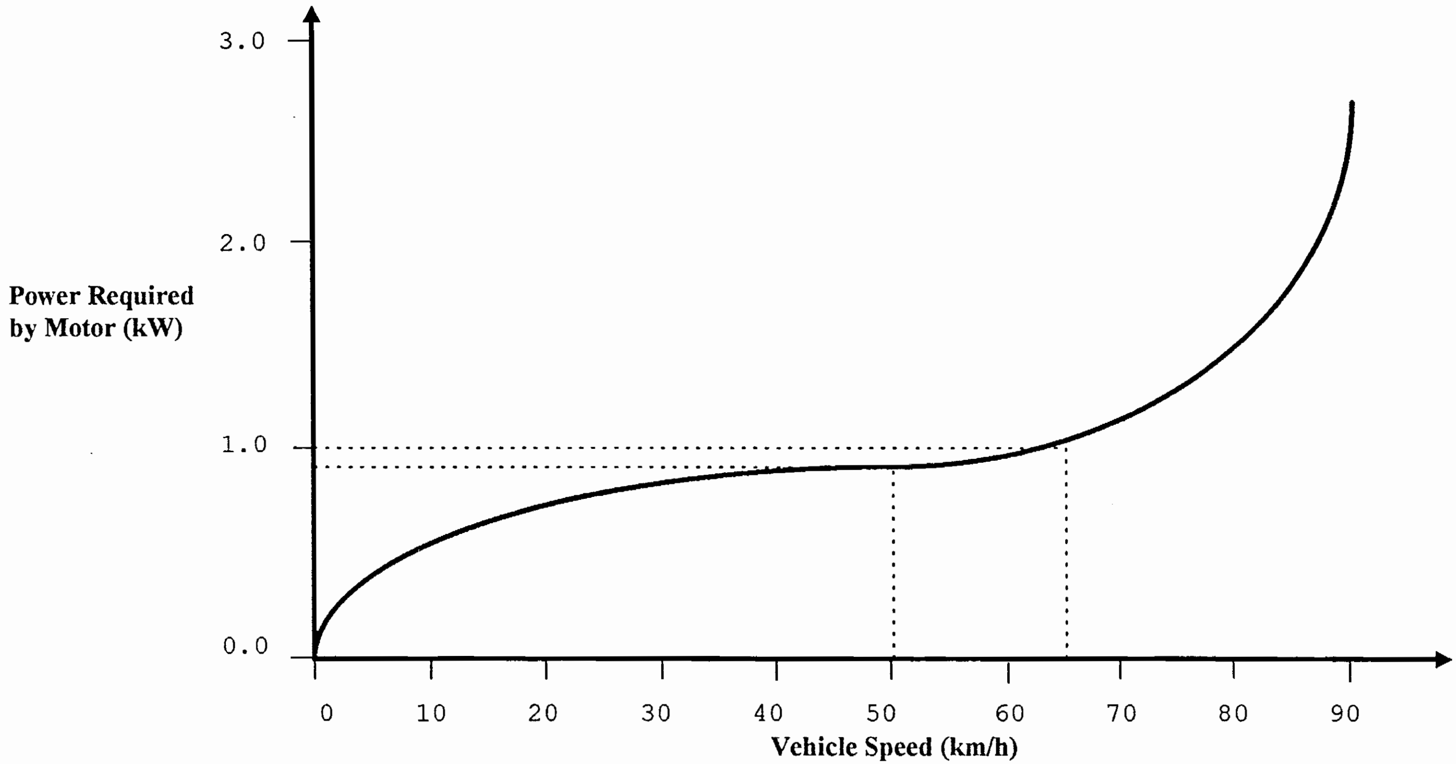
Various marketing and consumer behavior research has been used to study the car market from the demand, or customer viewpoint[5,7]. It has been clearly shown that the commercial car market is highly segmented, with many specialized needs in each segment. However the market as a whole shares many common attributes with respect to the car purchasing decision. Research has shown that a relatively large primary market of innovator-preference consumers, which accounts for almost 40% of the total domestic market for new cars[6]. These consumers show a medium to high affinity to the purchase of cars based on technological merits and concerns. This represents the baseline target market for solar powered cars. Cars must fulfill these consumers needs to have a chance in the marketplace.

Within the target market, many commonalties exist. For instance, over 80% of these consumers uses cars for commuter use only, each of with under 50 km daily round trip commuting range. Another statistic is that 50% of cars owned by this market are used for routine travel of under 100 km per week. Preference studies also show that these consumers typically purchase a second, standard performance car for this routine travel[7,8].

In marketing to these kinds of target markets, a general rule is that the product must satisfy the need of twice the intended primary market. This approximation will allow the producer to obtain a reasonable secondary market. The secondary market should typically reflect the order of magnitude of the basic market share. In other words, to compete on equal grounding in the solar power arena (assumed to be 10% of the manufacturer's fleet) the manufacturer must satisfy at least 20% of the market needs[5]. That figure is consistent with the ability to capture the market of secondary cars for commuter travel of approximately 50 km per day maximum. Thus the electrical system must provide adequate range and performance to satisfy these customers.

A profile has been specified by the mechanical system to relate the necessary power to the speed which can be attained on a flat surface. The characteristics are based on a 5 kW motor providing a similar acceleration response to a standard performance, commuter class car[6]. The electrical system in this profile is allocated 230 kg of weight. The power necessary for achieving specific speeds is shown in the profile of Figure 4. This profile relates the performance requirements to electrical storage and supply requirements.

Based on additional consumer studies, the maximum perceived marginal benefit of range in solar cars is found to be at least 650 km at an average of 65 km/h on stored energy alone. These figures are determined by asking potential customers to rate their willingness to purchase a car based on various attributes and life-cycle costs[7]. The perceived marginal utility of an attribute is derived from its demand elasticity to cost. The optimum value for that attribute may therefore be determined from the trade-offs which the respondents tend to make. Specifically, the range figure has been discussed by several focus groups[5,7,8].



<u>Figure 4 - Power Profile</u>

From these groups it has been determined that the utility was derived from the ability to drive at night, typically on occasional business or pleasure trips. Because charging the batteries is a slow process, the consumers preferred a higher range that typical for conventional cars.

The range as specified directly relates to the operational need for power storage in the car. For the car to travel at 65 km/h, the motor requires 1 kW of power. So for the 650 km range, the car must supply 1 kW of power for at least 10 hours. The battery storage requirement is therefore 10 kWh.

Another performance requirement is that the car be capable of indefinite travel at an average of 50 km/h in full sunlight. This means that under normal sunlight conditions, the car can travel at up to 50 km/h using only solar energy. The batteries in this scenario will not be drained of any energy to power the car. This is found to be desirable to consumers, since the time average speed of commutes in the target market is about 42 km/h. Therefore, on stretches when clear days far outnumber cloudy or rainy days, the car will not use any battery power, and thus may not need to be charged for several thousand km of travel. Above 50 km/h, consumers apparently expect to tap the battery power, and therefore are less willing to pay for additional capabilities[3,7].

This speed requirement indirectly specifies the power needed to be collected by the solar panel. Specifically, to travel 50 km/h, the motor requires 900 W of power. Thus the panel, in full sunlight must provide 900 W of power for the motor plus any additional power required for auxiliary devices such as brakelights.

In addition to the performance, consumers are also concerned about maintenance and reliability. In terms of reliability, the target market of consumers responded that the optimum marginal utility would be attained if the electrical system's overall reliability exceeds 80%[8]. The solar car electrical system must have the same life expectancy as a typical standard performance car. This expected life is approximately 10 years. Operation of the electrical system is considered to be continuous over this span, since the electronic equipment is continually collecting and managing power. The only additional stresses caused by driving the car are concentrated in the mechanical system. Therefore, the failure rate given the stated reliability must be less than 2.55 failures per million hours of operation.

Maintenance must also be considered within the electrical system. The mechanical system for a solar powered car is extremely efficient, and therefore relatively difficult to maintain. The maintenance of the electrical system must be accordingly less. The key aspect of maintenance to a potential customer is the amount of time that the car is unavailable due to maintenance. An appropriate measure for this attribute is called MMH/OH, or Mean Maintenance Hours per Operating Hour. Over the course of a year, the consumers require that the electrical system needs less than two full weeks of maintenance. Since the maintenance is to closely mimic a conventional car, as seen in the maintenance concept below, any maintenance is assumed to be performed 12 hours per day, 6 days per week. This implies 144 maintenance hours per year, or an MMH/OH of approximately 1.64%.

MAINTENANCE CONCEPT

There are three levels of maintenance performed on the electrical system: 1) Owner maintenance; 2) Dealer/Authorized Service Center maintenance; and 3) Factory maintenance. Owner maintenance covers simple scheduled and unscheduled maintenance which could be performed by a technically unskilled vehicle owner in the fashion of a "backyard mechanic" or road-side emergency. Scheduled maintenance at this level could include visual inspections or running simple self test diagnostics. Unscheduled maintenance could include replacement of solar panel modules with spares, similar to the changing of a tire. Service centers will carry stocks of solar panel modules as well as certain electronic modules.

At this point, it is necessary to differentiate between electronic devices, which can generally be grouped into power devices and control devices. Power devices tend to be physically larger, more sturdy, and less complex than control devices. Control devices tend to be smaller, more delicate, and more complex. Thus, it will be desirable to separate power devices from control devices in the system design. From a maintenance standpoint, the power devices will be replaced as spares at the service center level, whereas control devices will be provided by the factory. Fault isolation may be performed by the owner or service center by use of status indicators and self diagnostics.

Much like with current commercial vehicles, the service centers will be provided with spares of the power electronics modules. It is expected that these modules will require no specialized tools for removal or replacement. The labor required for this maintenance will typically be less than for an equivalent mechanical maintenance action, since the electrical system need not be structurally secured to the mechanical system. These power modules also require little special handling, hence easily stored in an inventory at a service center. The service center, once it replaces a module, the faulty module is delivered to the factory for possible repair or salvage of parts. Further analysis will determine whether faulty modules will be repaired, discarded, or salvaged for components.

The third level, factory maintenance, includes the repair and replacement of the control modules. These modules are expected to be housed in a common physical enclosure, with no special tools required for removal of the entire set. However, within the enclosure, there may be specialized connectors and delicate electronics, which require highly skilled labor to perform fault isolation and replacement. In practice, the vehicle owner will not want to wait over two weeks for the repairs, so spares held at the factory will be delivered on request to the service center where the owner has brought the vehicle. The service center will be able to replace the working set using no specialized tools. The spares maintained at the factory can be reassembled from salvaged working components of several other faulty sets. Faulty components from the control units will be discarded, due to their highly complex and delicate nature. Figure 5 summarizes the maintenance concept.

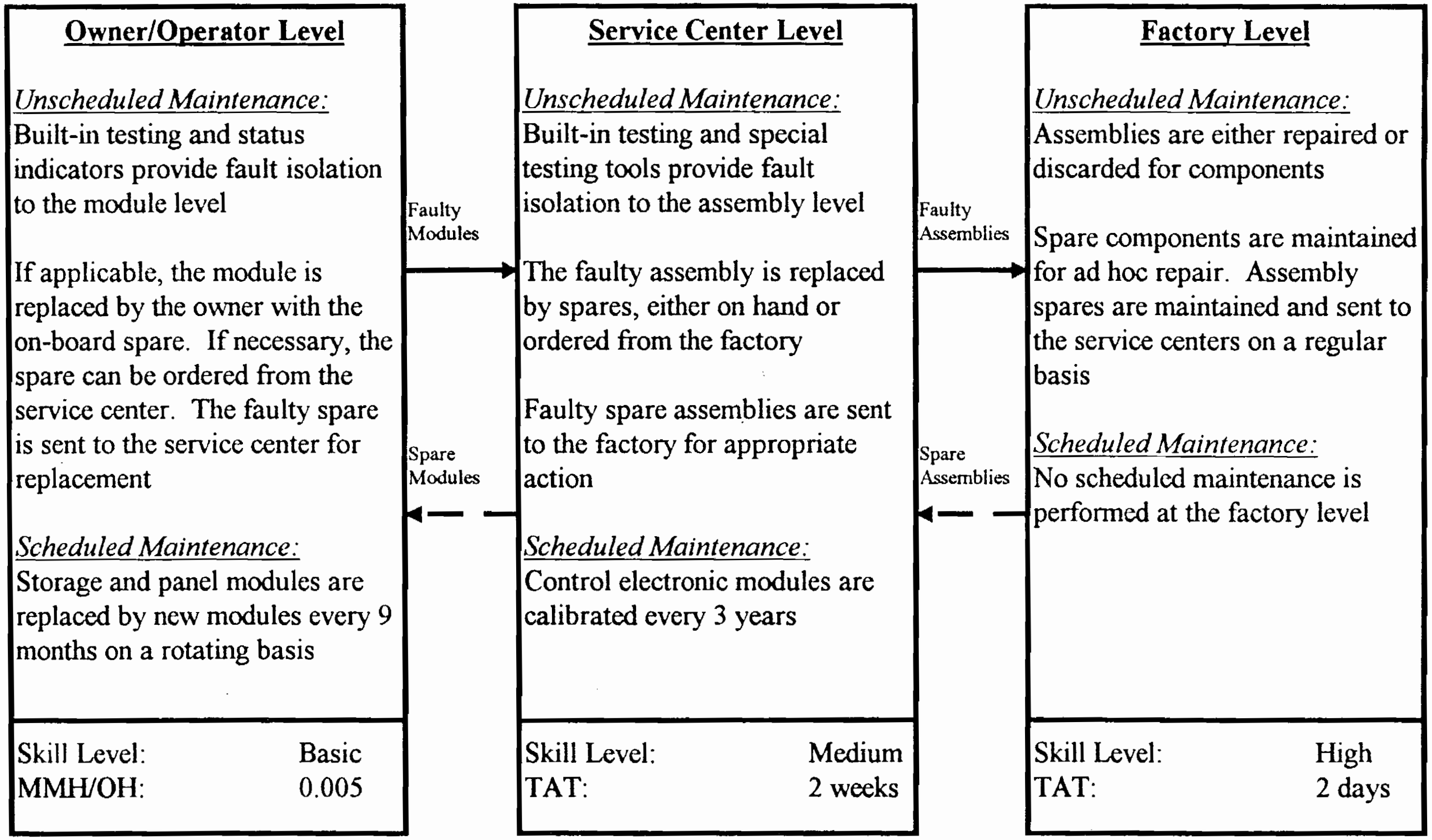


Figure 5 - Maintenance Concept

FUNCTIONAL ANALYSIS

The functional analysis begins with the system level functional requirements. Figure 6 depicts the initial functional flow for the operation of the system. Collection of solar power is implicit in the system functional requirements. Since there is a distinction in the functional requirements between driving and parking, there must be functions for transitioning between the states as shown. The two requirements for providing power are combined into one functional block at this point for simplicity. Finally, because there is a requirement to drive at night, there is an implicit requirement to manage the power collected during daylight hours. The power management function also includes providing status to the operator. This level of functional flow covers all of the system level requirements, but must be further decomposed into more specific functions to allow the allocation of physical resources against the requirements.

The functional flow in Figure 7 is derived from the power collection function. In order to provide useful power, the energy from the sunlight must be converted to

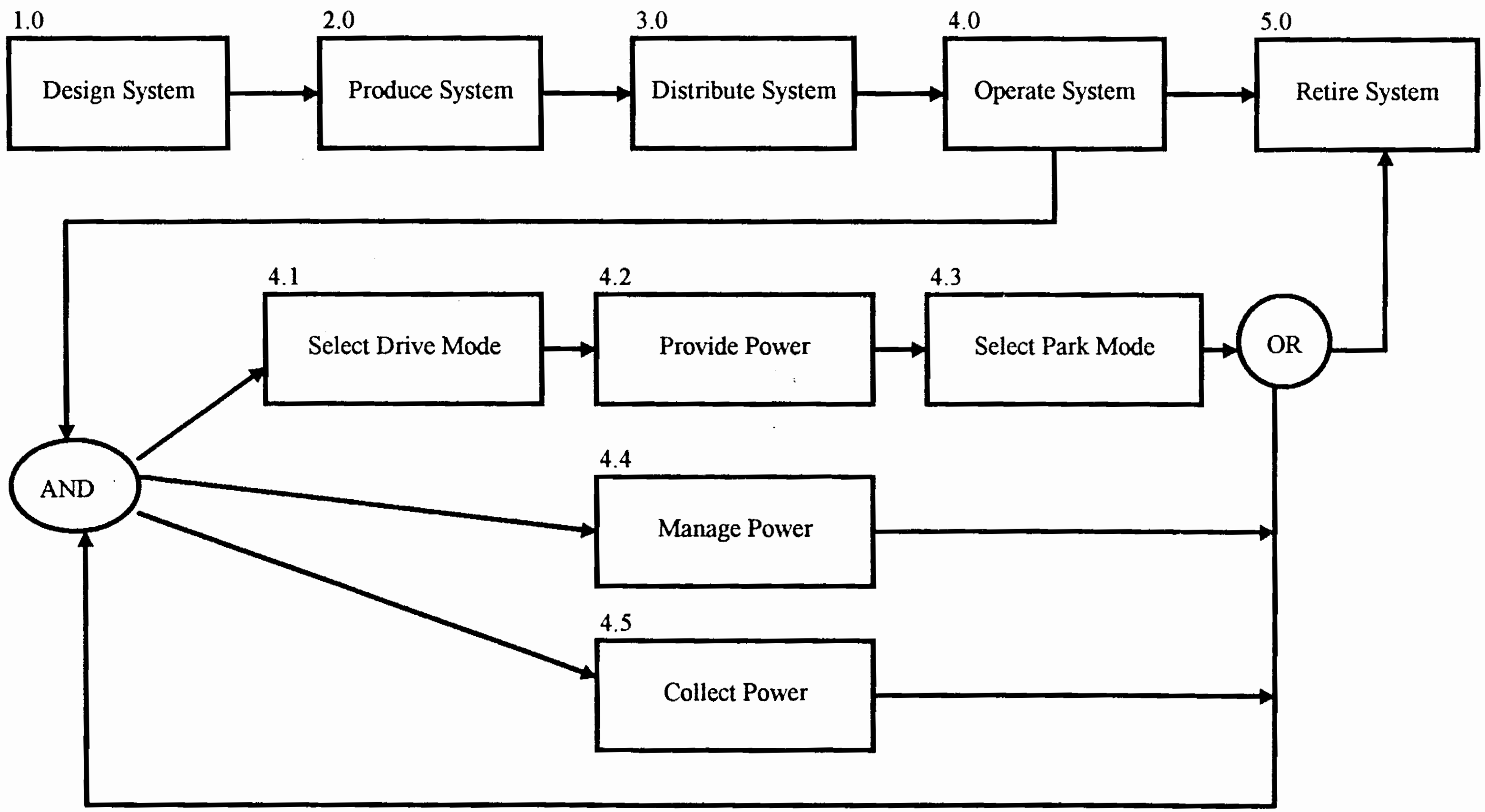


Figure 6 - Initial Operational Functional Flow

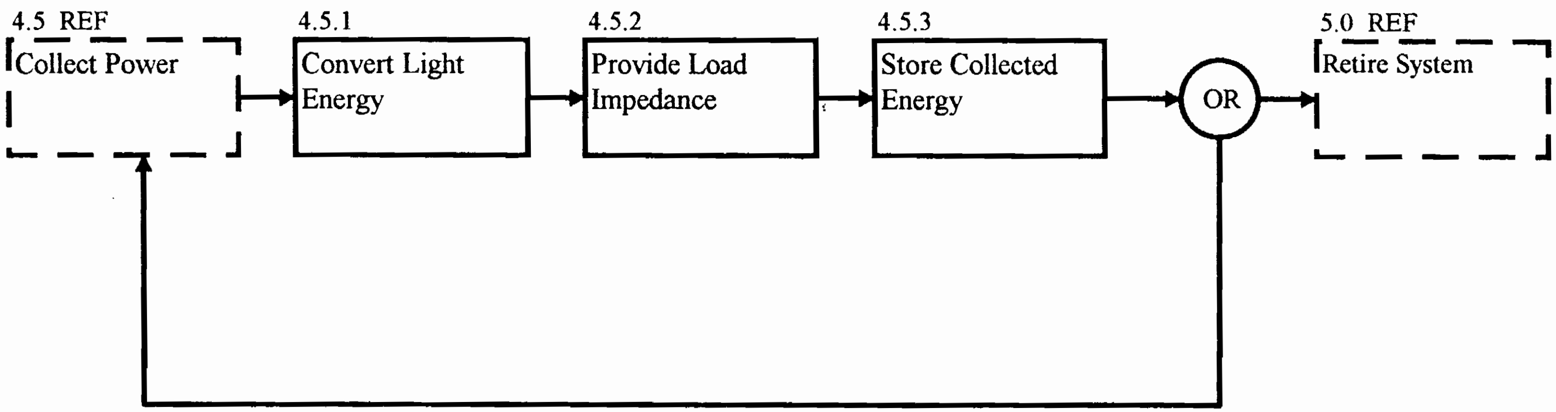


Figure 7 - Collect Power Functional Flow

electricity. As the power is generated, it creates a voltage potential which must be loaded by an impedance to be utilized[10,11]. Further, this power must be stored if it is not immediately used.

Figure 8 depicts the functional breakdown of the manage power function. Manage power accepts input from the storage elements as well as directly from the motor. This power from the motor is called regenerative breaking, and is mechanically analogous to engine breaking in a conventional engine. This technology allows the motor to act as a generator to transfer the momentum of the car into electricity[4,12]. The input powers are summed, and the result is loaded by an impedance from the provide power function. Any excess power is routed back to the storage elements. Throughout the power management function, there is a function which provides status feedback to the user. This function is broken into the subfunctions shown in Figure 9. The status function must sense various values, calculate the range and available storage, and display the output to the operator.

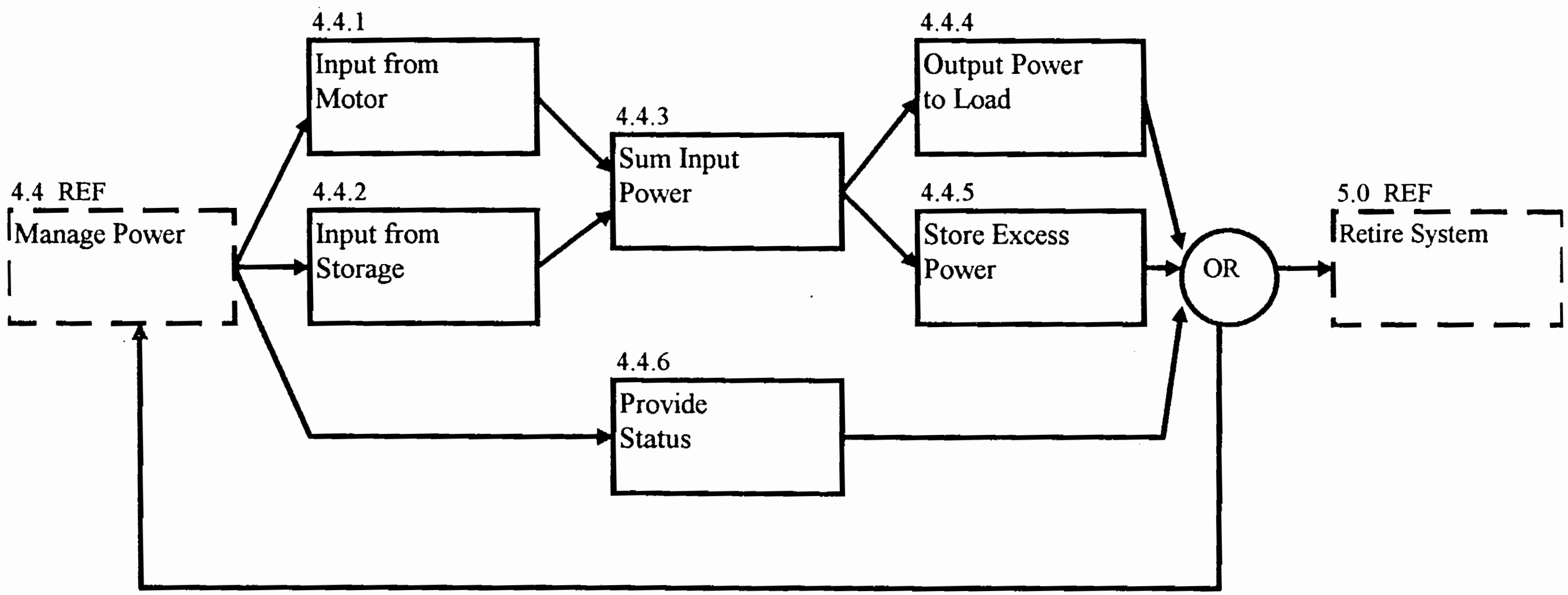


Figure 8 - Manage Power Functional Flow

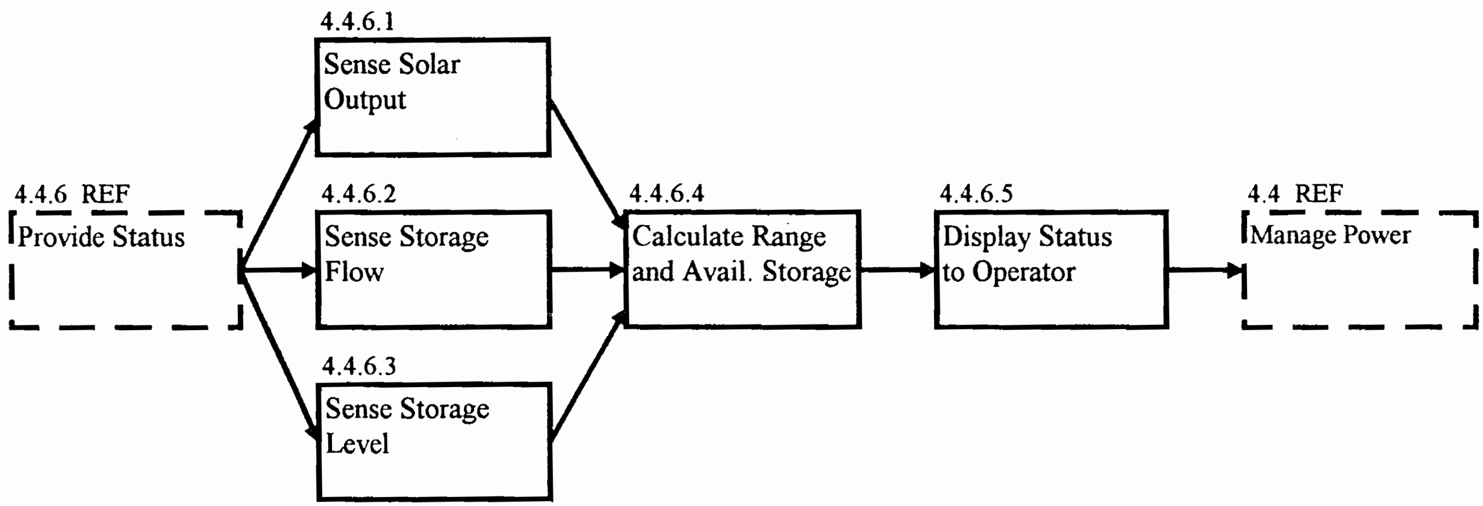


Figure 9 - Provide Status Functional Flow

The provide power function is depicted at a high level in Figure 10. Although there are many functions, each is relatively basic in nature. However, the provide motor control function is further broken down in Figure 11, where it is shown that there are three operating modes identified for the solar car. Acceleration pedal mode and speed cruise mode are directly derived from conventional car interfaces, and therefore provide similar functions. A power cruise mode is derived to allow the operator to select a constant net drain on the storage elements. The speed of the car in this mode is adjusted to maintain this drain. This mode provides many advantages specific to solar cars, such as extending the range of the batteries by limiting peak power drains. Additionally, the operator may set the control for a net zero drain on the storage elements to rely completely on collected solar energy, or set a negative value to continuously charge the storage elements. In each of the operating modes, there is a function to sense system variables, calculate a desired speed setting, and output the control signal to the motor.

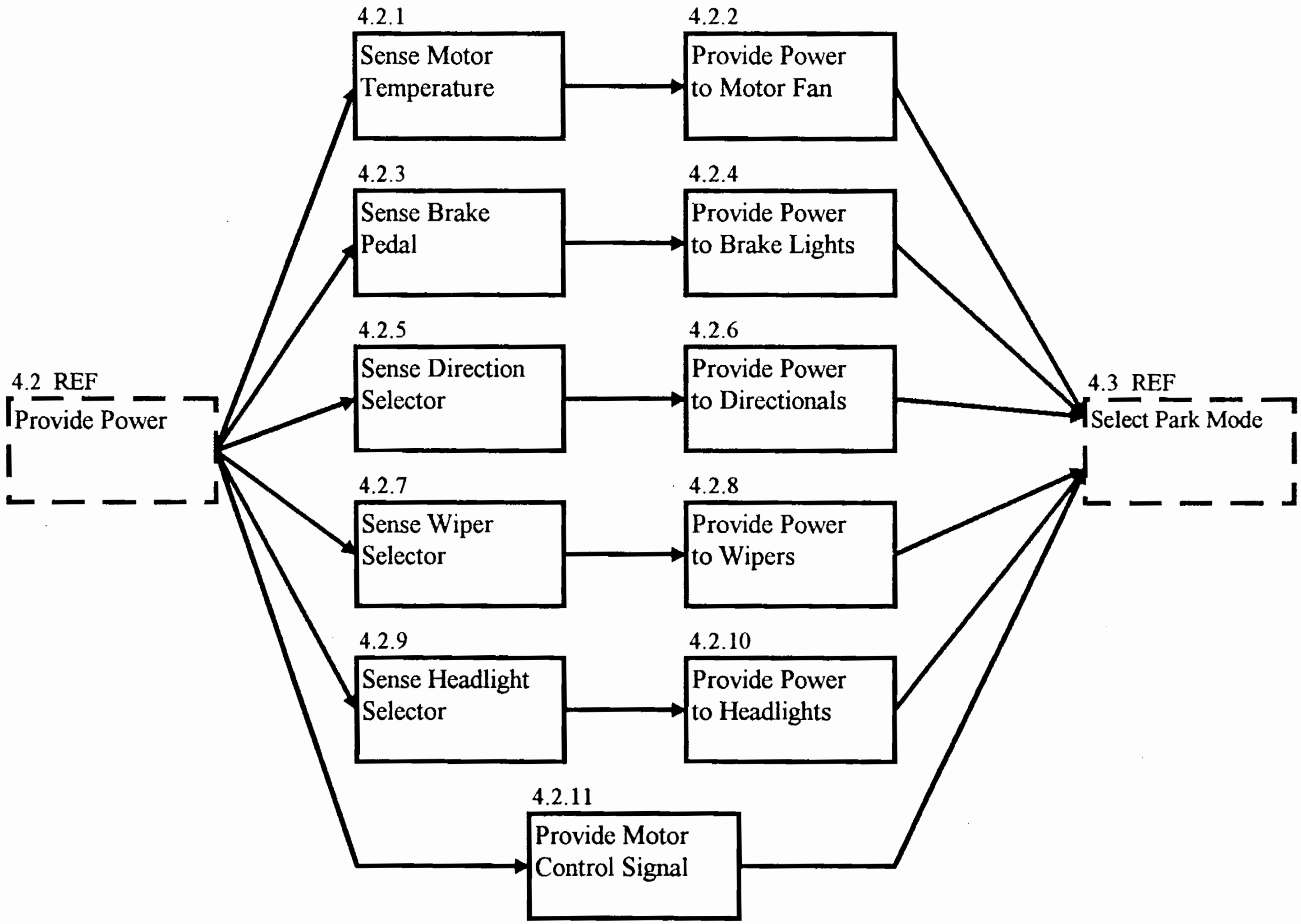


Figure 10 - Provide Power Functional Flow

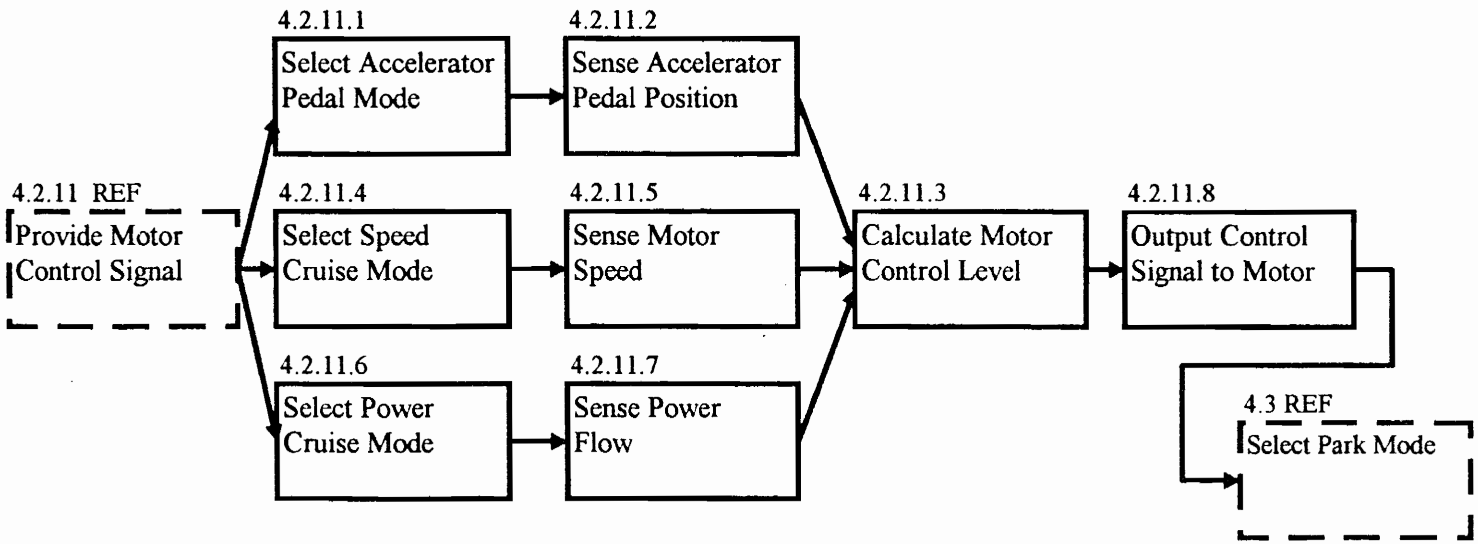


Figure 11 - Provide Motor Control Functional Flow

In addition to the normal operation of the system, there must also be a consideration for the maintenance of the system. Figure 12 depicts the maintenance flow of the system for troubleshooting when the car does not start. The maintenance flow is based on the maintenance concept described earlier and ties in to the functional flow as shown. Also, the ultimate problem causing the car to malfunction may lie in the mechanical system. Hence the diagram shows an indication that the appropriate maintenance flow must be followed in this case.

At this point in the design phase, the functional flow has been decomposed to a level appropriate to package in physical assemblies. This specification of design resources to the functional analysis comprises the system synthesis.

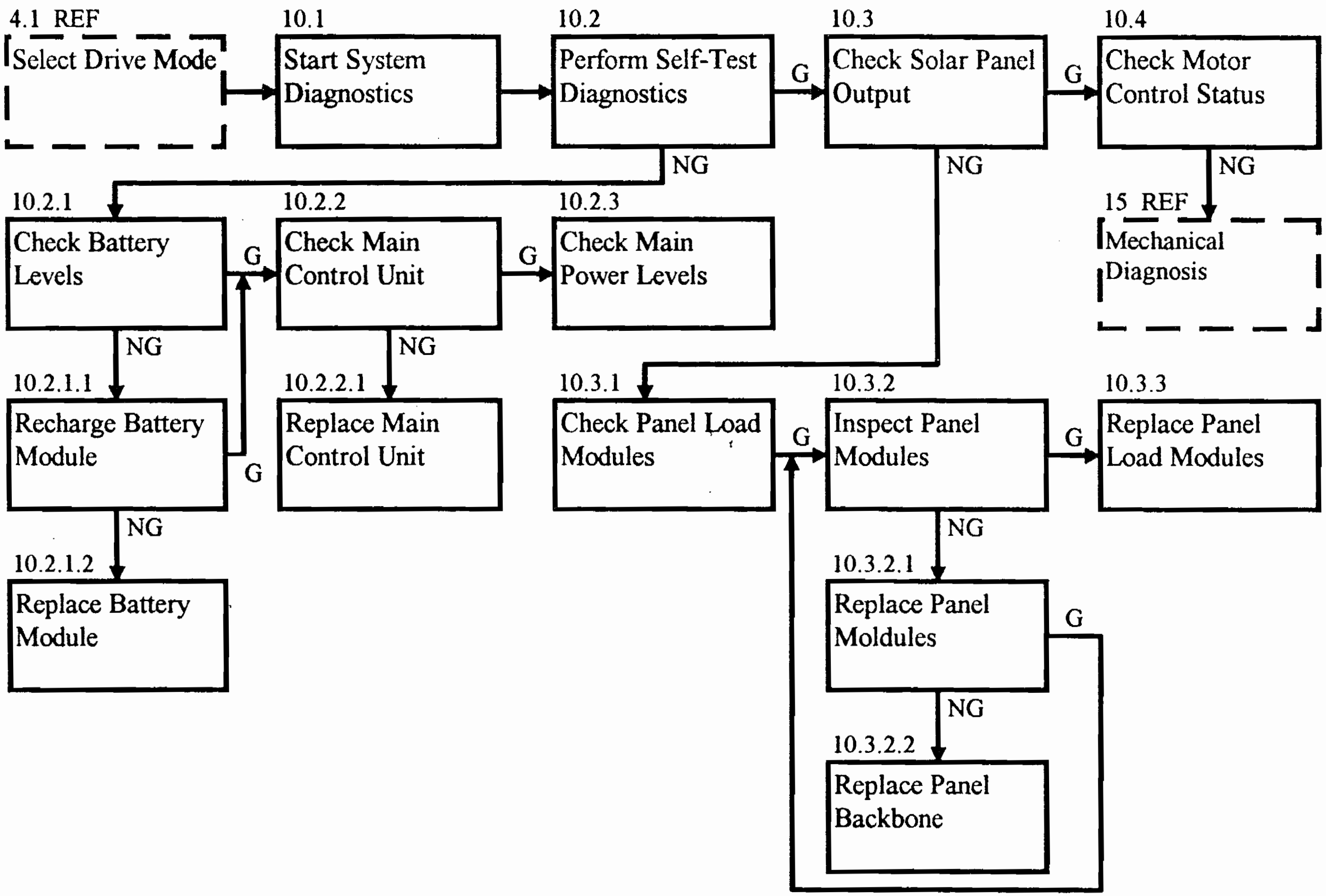


Figure 12 - Maintenance Flow

PRELIMINARY SYSTEM SYNTHESIS

An initial breakdown of the electrical system is taken from the nature of electrical technologies involved. Namely, there is an inherent difference between power electronics and control electronics, and either is significantly different from the solar collection circuitry which relies on specialized hybrid electronics. It is appropriate to note that the maintenance concept described below not only supports this breakdown, but benefits from it. Another feedback from the maintenance concept is that the panel should be modular in nature, with interchangeable modules. This architecture is supported by separating the panel subsystem into solar collection elements and backbone elements, as shown in Figure 13. In order to prevent the failure of a solar module to result in backward loading of other modules, protection circuitry is provided as an assembly within the modules. The backbone control assembly is derived from the control subsystem, described below.

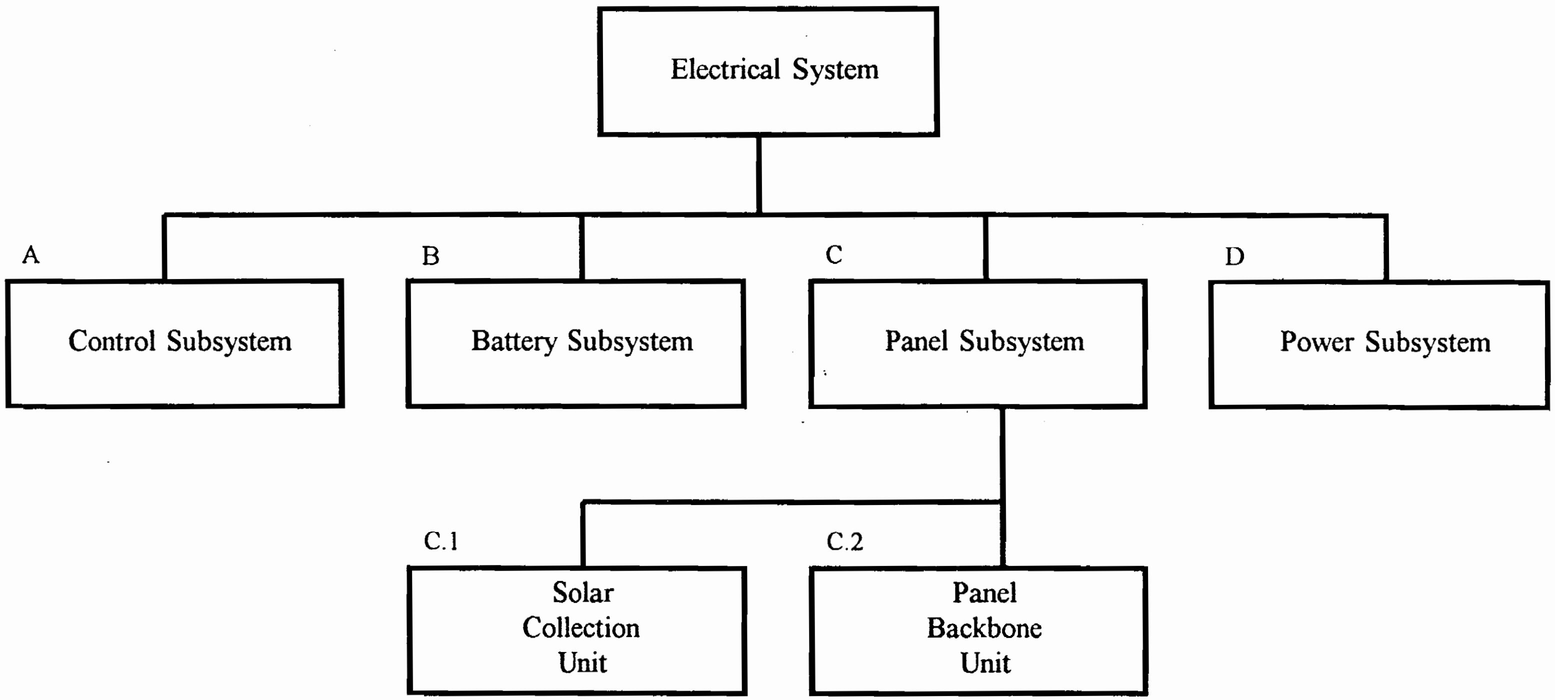


Figure 13 - Panel Subsystem Synthesis

The control subsystem, which mainly calculates values or logic states, can be realized in several forms, the most electrically efficient two being discrete analog circuitry and digital circuitry. It is necessary to perform a trade-off analysis to select an alternative, since further requirements allocation varies significantly depending on the selection. From an electrical standpoint, both digital and analog solutions will maintain adequate accuracy for the calculations, and each utilizes a nominal amount of power to perform its functions. However, the systems approach requires that the entire system be examined for possible impact. The analog solution requires discrete components for each calculation, whereas the digital solution requires a processor unit with discrete software parameters for each calculation. Any upgrades, modifications, or maintenance to the control subsystem in the digital case could be completely contained in software, presumably based in a programmable read only memory. The digital approach also allows an efficient power tracking assembly, to be included in the solar modules, which loads the solar modules at their most effective impedance. Analog power trackers are relatively unreliable and inefficient compared to the digital counterpart. The choice of a digital solution implies both hardware and software components of the control systems, plus an allowance for input ports for the sensors. The subassembly level is shown in Figure 14.

The power subsystem, shown in Figure 15, is relatively simple. It consists of the the main power bus, and power switches. The main power bus contains assemblies for both the motor bus and an auxiliary bus, which maintains power for the auxiliary functions.

Next is the final step which includes an analysis of system level requirements as they are traced throughout the system. Additionally, the maintenance concept and manufacturing plan, each of which is documented, are followed by a requirements allocation.

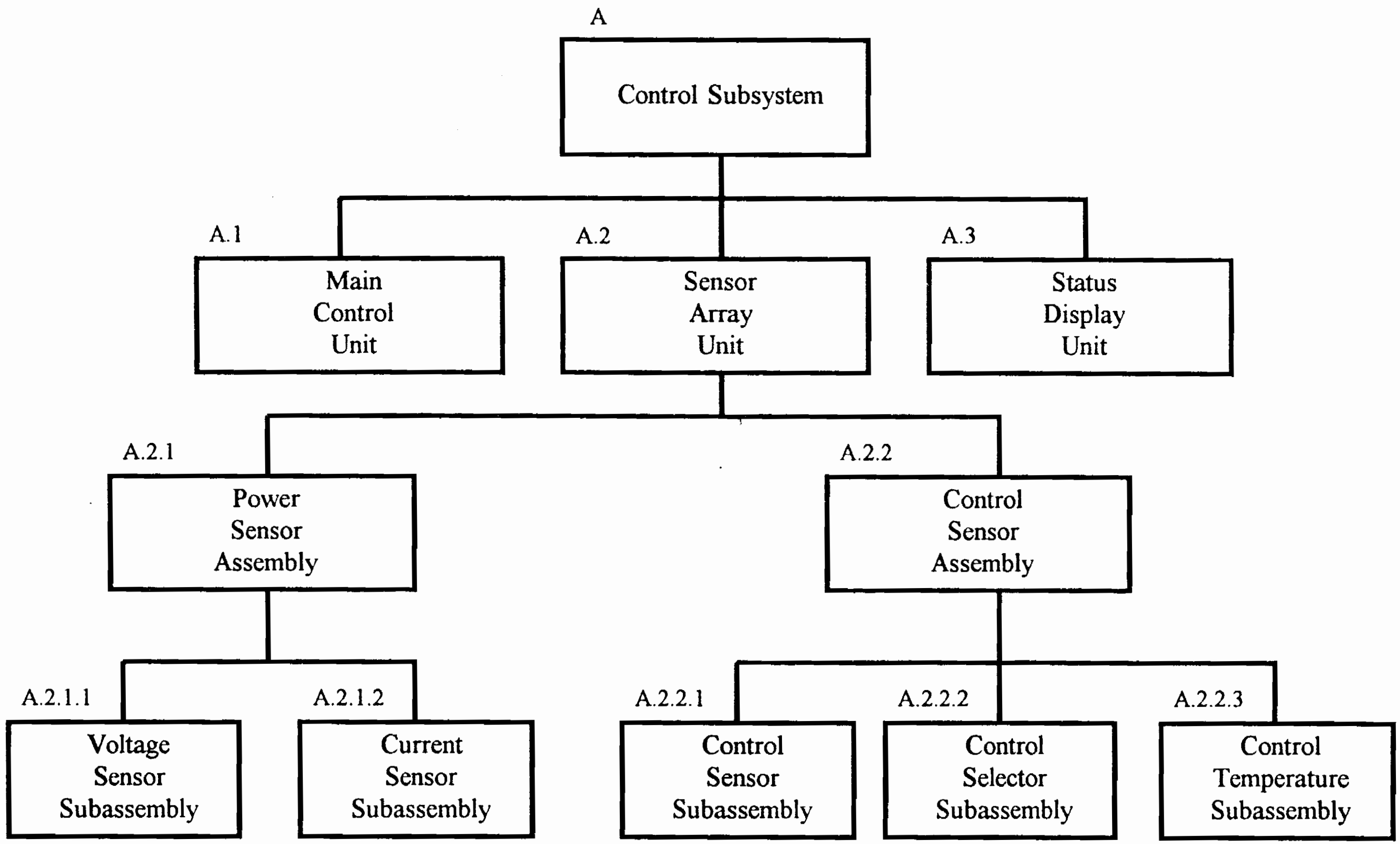


Figure 14 - Control Subsystem Synthesis

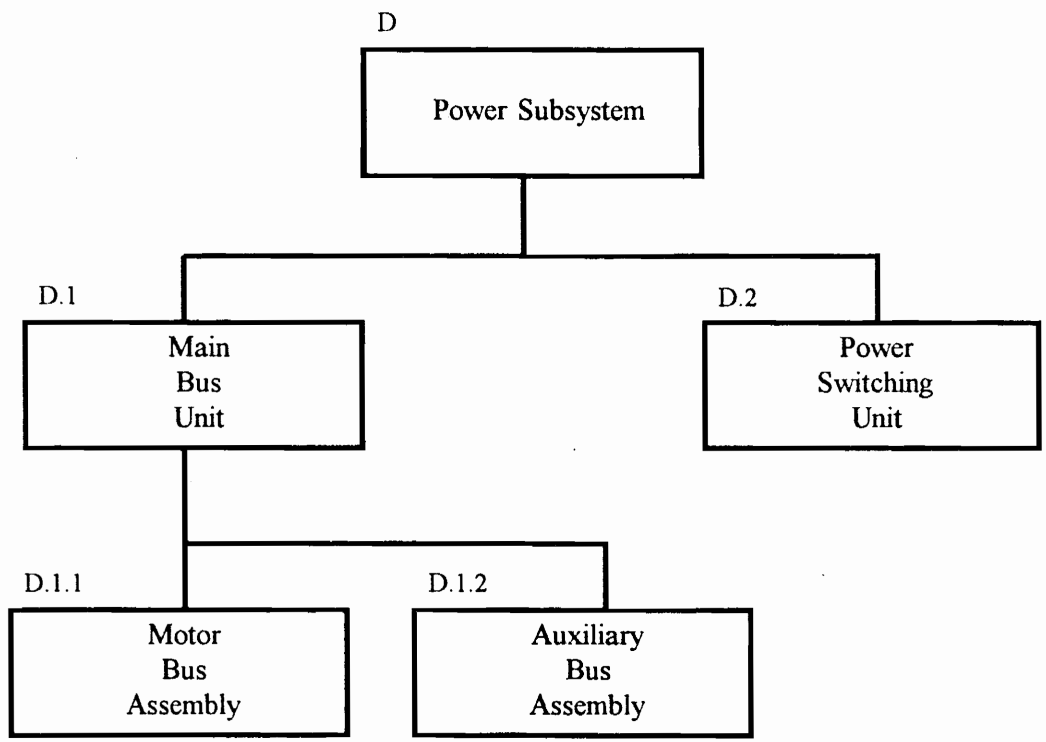


Figure 15 - Power Subsystem Synthesis

REQUIREMENTS TRACEABILITY

This process ensures that all of the functions identified in the functional analysis are fulfilled by the system specification. Although there are many instances where the functional blocks are achieved by specific design blocks, it is not necessary that the mapping be one to one. In other words, it is likely that several functional requirements may be satisfied by one assembly, whereas many other assemblies may be required to satisfy one other functional requirement. A traceability diagram, showing the functional packaging of requirements, is shown in the several pages of Figure 16. The diagrams depict the functional blocks on the top mapping to physical asseblies from the synthesis process on the bottom.

The traceability diagram does not ensure that the operational requirements are all met by the design. The requirements allocation, described below, assigns specific system level requirements to the various lower level design elements. This ensures that each subsystem has a specific design goal in terms of the overall system requirements.

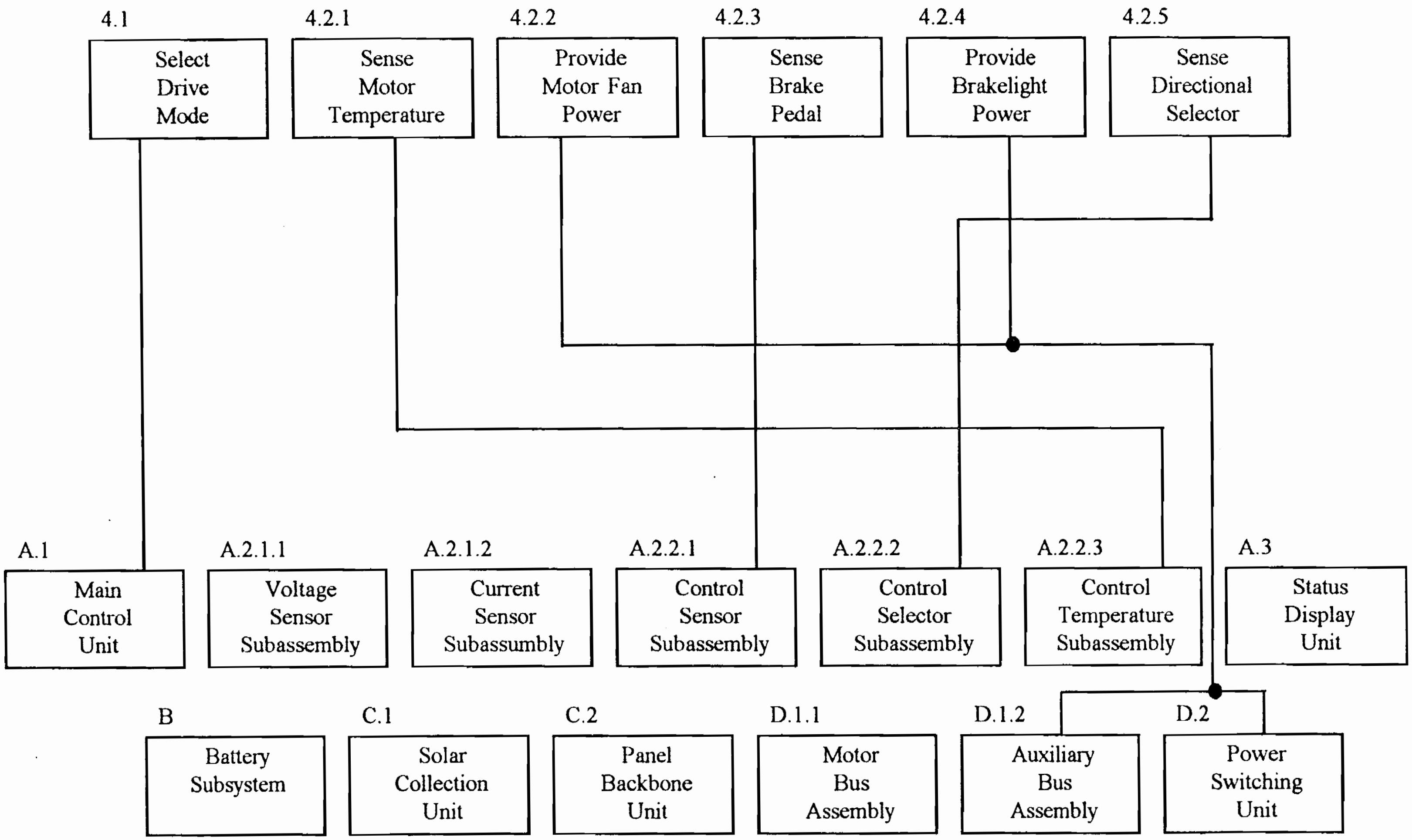


Figure 16(a) - Requirements Traceability Diagram

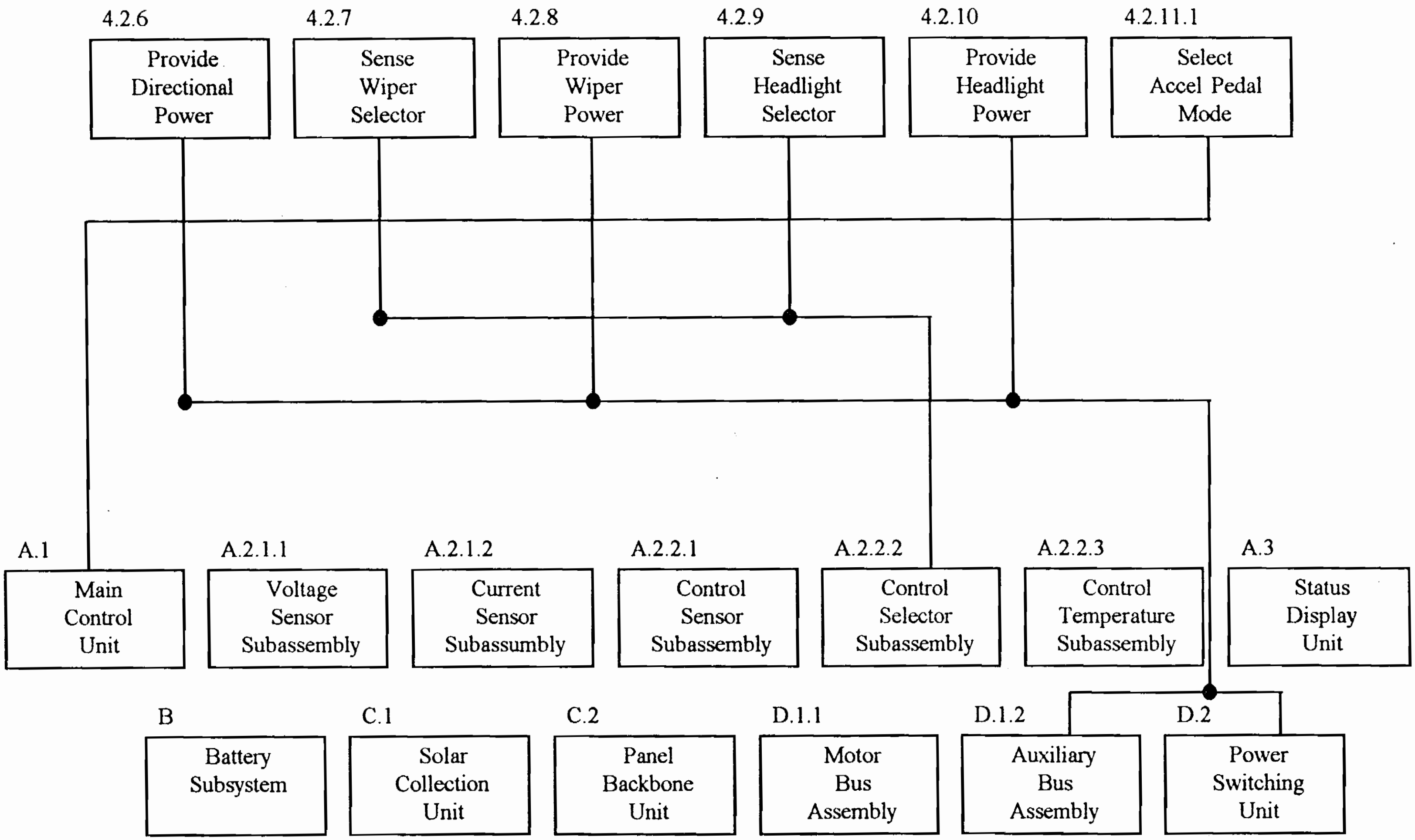


Figure 16(b) - Requirements Traceability Diagram

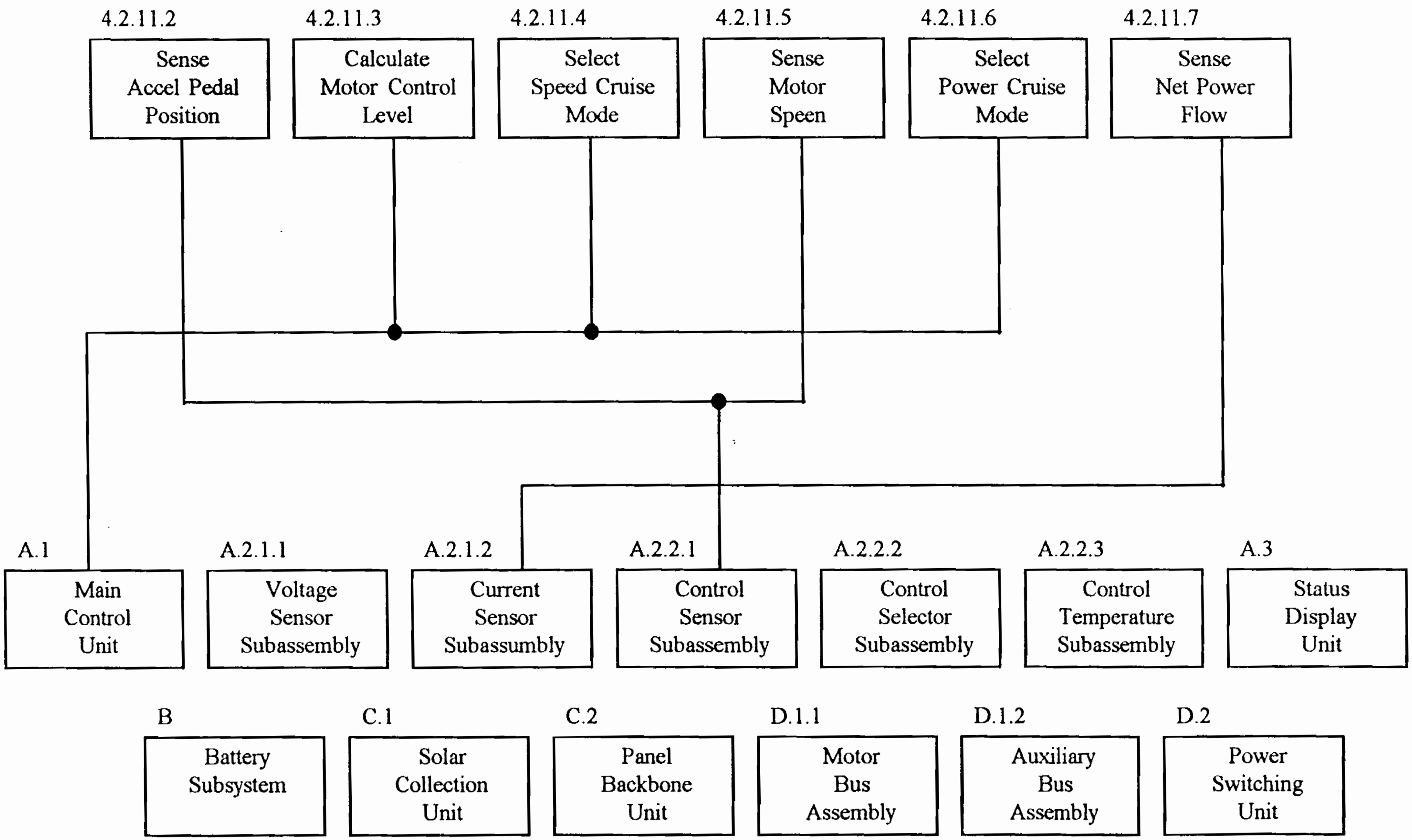


Figure 16(c) - Requirements Traceability Diagram

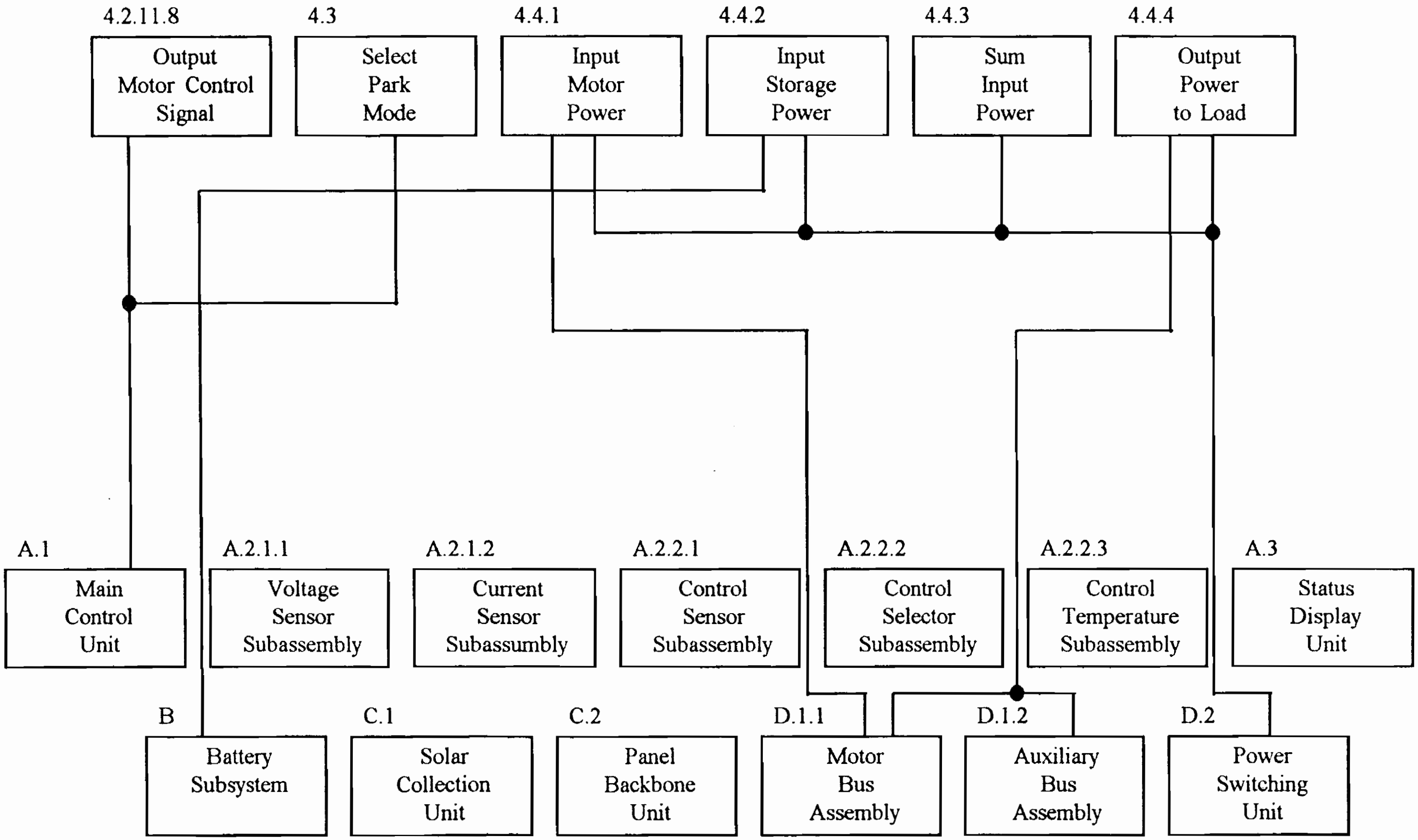


Figure 16(d) - Requirements Traceability Diagram

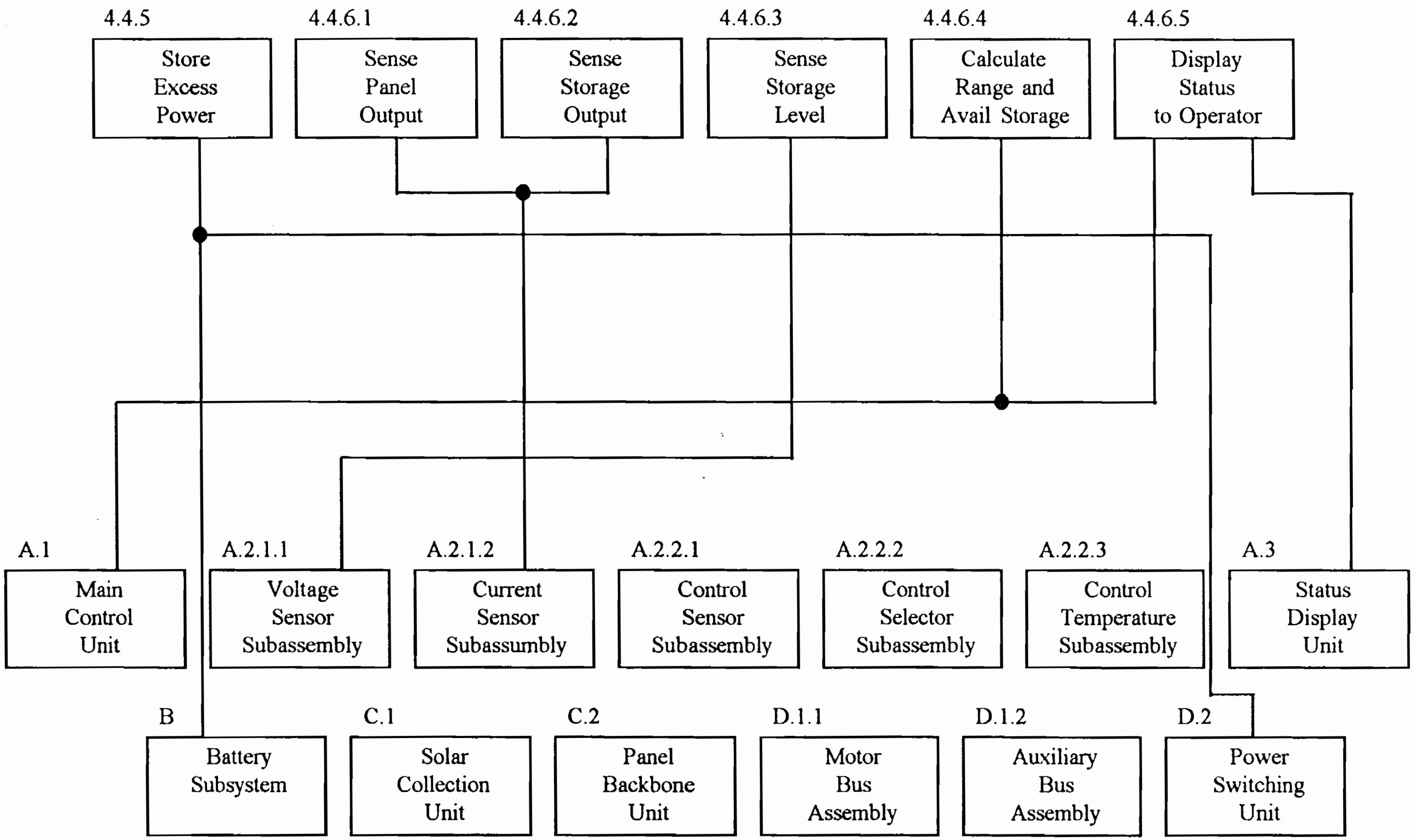


Figure 16(e) - Requirements Traceability Diagram

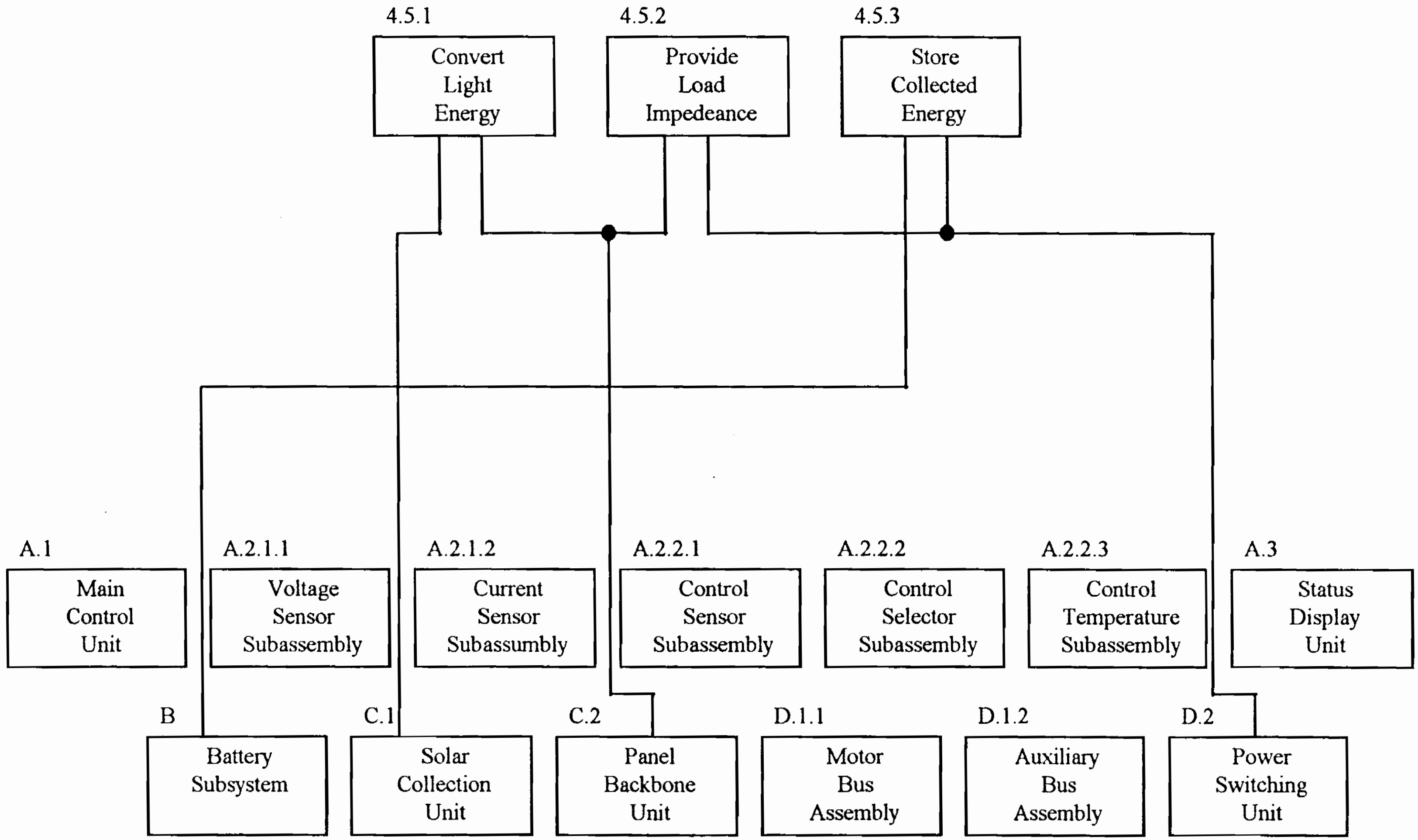


Figure 16(f) - Requirements Traceability Diagram

REQUIREMENTS ALLOCATION

The primary factors traced throughout the system are weight, electrical power, electrical storage, reliability, failure rate, and maintenance rate. The system allocations are shown in Figure 17. From the allocation, the batteries may weigh up to 200 kg to fit the mechanical profile from Figure 4. Based on the range requirements and the power profile, it was determined above that the batteries must supply a 1 kW of power to maintain the specified speed for 10 hours. Therefore, the storage requirement is at least 10 kWh of energy at the 10 hour discharge rate. A high discharge rate negatively affects the battery capacity, but at this rate this effect is minimal. The storage capacity of 10 kWh allocated over 200 kg of mass implies an energy density requirement of 50 Wh/kg[4].

Currently, common lead acid batteries maintain an adequate energy density to fulfill the requirements, while new innovations such as silver zinc batteries more than double the energy density requirement[9].

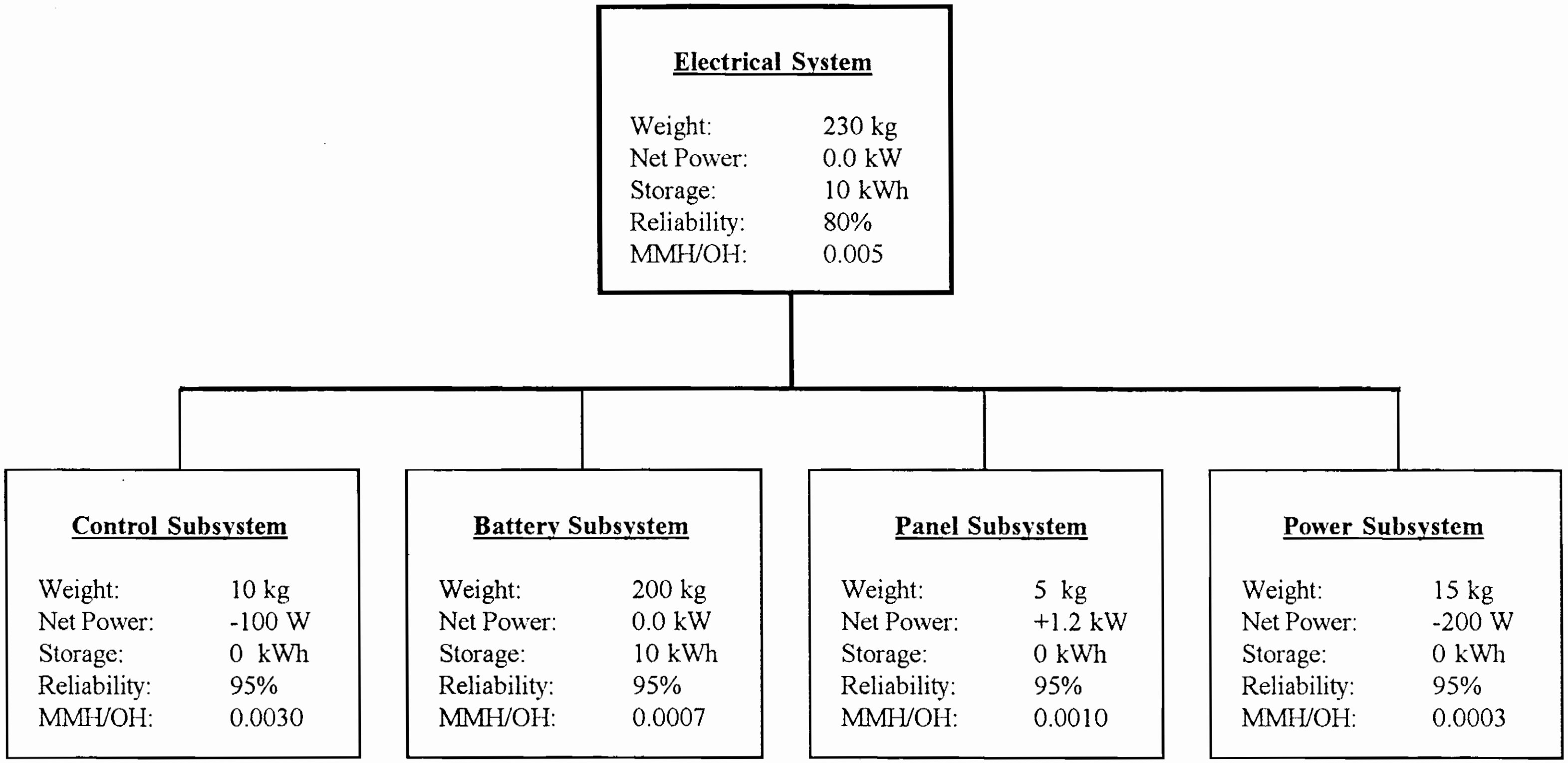


Figure 17 - System Level Requirements Allocation

This implies that further trade off studies must be performed to compare the cost versus benefit of the various battery choices. Life-cycle cost including maintenance and consumer acceptance are the key figures of merit for the trade, where the more efficient batteries may provide sufficient perceived benefits, such as range and speed, to warrant the extra cost.

Because the net power use of the electrical system must be zero, the solar panel must generate sufficient power for the motor to operate at the required speed on daylight alone. The system must also power the control and auxiliary devices. Based on the power profile, the motor requires 900 W of power to maintain this speed. From the requirements allocation it is determined that the must provide at least 1.2 kW typical power in daylight. The solar collection area is assumed, as stated above, to be 12 m^2 in area. Typically in terrestrial applications it is assumed that normal sunlight provides approximately 1000 W/m^2 of useable power[3]. Only a portion of this light energy can be successfully converted to electrical form. In fact, the given specifications imply a total effective conversion efficiency of 10% required over the entire collection area to provide 1.2 kW of power. Since typical terrestrial grade cells achieve 12% efficiency while space grade cells achieve over 16%, there will be a range of solutions which will meet the requirements[4,6]. Therefore a trade study must be performed on the solar modules based on life-cycle costs, including maintenance, versus perceived benefit.

In addition to these performance requirements, the system level maintenance and reliability requirements must be allocated to every level of the system specification. These are also shown on the requirements allocation diagram. Once all of the requirements have been allocated, a system optimization, as described below, is performed to determine the overall makeup of the system elements. This information is utilized as a feedback to determine if the requirements can be satisfied by the proposed allocation.

SYSTEM OPTIMIZATION

One of the many system and component level optimizations which can be performed is a trade study which determines the amount of redundancy required for each component of the system. For example, the solar collection panel can be designed as one complete unit, or segregated into many parallel units. This does not necessarily imply parallel as in the electronics definition, but rather in the reliability sense. That is, if the panel is constructed as a single unit, any single failure in the panel will cause the panel as a whole to fail. If, on the other hand, the panel is constructed as two parallel units, a single failure would not disable the entire function.

In performing the optimization, a figure of merit is required which adequately measures the trade space of the possible alternatives. Because power is the most important system design factor, an appropriate figure of merit is based on the marginal reliability as a function of the associated power loss. The source of this loss is in the inefficiencies present in all electronics, coupled with the loss specifically attributable to the electronics necessary to manage the redundancy[11].

Assuming the highest grade space cells are utilized for the panel, up to 720 W of power may be lost in the addition of redundancy. The reliability for the system, as stated in the requirements, must be at least 80%. Based on initial reliability estimates of each set of elements, in addition to the power loss caused by redundancy, the figure of merit is calculated for each possible unit and configuration. These calculations are shown in Table 1.

Next, starting with a baseline configuration of one component for each unit, additional components are added based on maximum figure of merit calculations. These redundant components are added until the reliability exceeds 80%, or the power loss exceeds 720 W. In the latter case, the system cannot satisfy the system requirements as designed, and must be redesigned. The optimization process is shown in Table 2.

Table 1 - Reliability Optimization Worksheet

	POWER	PANEL	BATTS	CONTR
Loss *R-1*	*80 W* *0.85*	*25 W* *0.55*	*100 W* *0.95*	*15 W* *0.45*
R-2 **FoM(2,1)**	0.978 **0.76**	0.798 **6.46**	0.997 **0.21**	0.698 **12.69**
R-3 **FoM(3,2)**	0.997 **0.11**	0.909 **2.27**	1.000 **0.01**	0.834 **5.16**
R-4 **FoM(4,3)**	0.999 **0.02**	0.959 **0.93**	1.000 **0.00**	0.908 **2.49**
R-5 **FoM(5,4)**	1.000 **0.00**	0.982 **0.40**	1.000 **0.00**	0.950 **1.28**
R-6 **FoM(6,5)**	1.000 **0.00**	0.992 **0.18**	1.000 **0.00**	0.972 **0.68**

Table 2 - Configurations for Reliability

	FoM	Configuration	Loss (W)	System Reliability
Initial	N/A	1 1 1 1	0	20.0%
add CONTR	12.69	1 1 1 2	15	31.0%
add PANEL	6.46	1 2 1 2	40	44.9%
add CONTR	5.16	1 2 1 3	55	53.7%
add CONTR	2.49	1 2 1 4	70	58.5%
add PANEL	2.27	1 3 1 4	95	66.7%
add CONTR	1.28	1 3 1 5	110	69.7%
add PANEL	0.93	1 4 1 5	135	73.5%
add POWER	0.76	2 4 1 5	215	84.6%

As can be seen from the optimization results, the system design can meet both the performance and reliability requirements. The system reliability for the final configuration is 84.6%, which exceeds the required 80% without an unacceptable loss. The final reliability configuration is 2 separate power electronic units, 4 separate solar panel units, 1 battery unit, and 5 separate control electronic units. This configuration corresponds to a total power loss of 215 W, which is less than the maximum allowed by the requirements. Thus the selection of cells for the panel may be a combination of space grade and terrestrial grade cells.

Specifically, a mix of at least 30% space grade cells must be utilized to meet system requirements. To verify this, it can be seen that the effective efficiency of the panel array is (0.7)(0.1)+(0.3)(0.16), which is equal to %11.8. This yields a panel power of 1,416 W over the entire allocated area. So with the additional 215 W loss, the net panel power meets the 1.2 kW requirement at an 80% system reliability.

LIFE-CYCLE COST ANALYSIS

The electrical system designed is for commercial use as a commuter car, and thus may be analyzed on a cost to the consumer basis. As a worst case for the car manufacturers, the cars containing this system can be sold at cost. Hence the manufacturers will not make a profit on the car, but will be able to satisfy the legal requirements and not incur a loss. Approximate electrical system construction costs are shown in Table 3[3,6,8]. The final cost of $10,075 includes an estimated allowance of 30% for labor, which assumes an assembly line production, using idle factory time and equipment resources[8]. This is the smallest price a consumer would pay for the electrical system alone. The price of the mechanical system would need to be added to obtain the total minimum sales price of the car.

The life-cycle cost of the system is based on the initial and maintenance costs throughout the system life. These costs are discounted by the estimated interest rate, assumed to be 7%, to account for the time value of money. The life-cycle calculations are detailed in Table 4.

Table 3 - Initial Production Cost Estimates

Power Subsystem		$ 400
Panel Subsystem		$ 2,600
- Space grade cells	$1,200	
- Terrestrial cells	$1,400	
Battery Subsystem		$ 4,000
Control Subsystem		$ 750
Labor		$ 2,325
TOTAL COST:		**$10,075**

Table 4 - Life-Cycle Cost Analysis

Purpose	Unit Cost	Present Value*
Initial Cost	$10,075	$10,075
Panel Maintenance - every 6 months	$ 240	$ 3,395
Battery Maintenance - every 12 months	$ 600	$ 4,170
Control Maintenance - every 3 months	$ 60	$ 1,712
Power Maintenance - every 12 months	$ 120	$ 834
ELECTRICITY COSTS - every 1 month	$ 1	$ 861
NET PRESENT VALUE:		**$21,047**

*Present Value based on a 10 year life at a constant 7% interest rate.

COST-BENEFIT ANALYSIS

There is typically no significant maintenance performed on the electrical system of a conventional car. The engine, transmission, and all other major maintenance are considered part of the mechanical systems. However, there is a significant savings obtained by the solar powered car, in lifetime fuel costs. More specifically, the electricity costs of the solar powered car replace any fuel cost over the lifetime of the car[7].

For a standard commuter car of the target market, a great majority of the consumers will drive between 12,000 and 16,000 km per year[5,8]. In the average 10 year life of the car, then, the consumer expects to travel approximately 140,000 km. Assuming even a conservative 8 km/l fuel efficiency, the consumer will purchase only 17,500 liters of fuel over the life of the car. Additionally, these purchases will be spread out over the life of the car, making the present value cost of the fuel even less.

Given a 7% interest rate, and equal fuel purchases every 2 weeks at a real cost of $0.30 per liter, the purchases will each cost approximately $20. The present value of these expenditures, and thus the cost of the equivalent electrical system in a conventional car, over the life of the car is $3,773. This figure is clearly less that the present value of the electrical system for the solar powered car. This cost savings may be realized in a less expensive life-cycle cost for the mechanical system of the solar car. Additionally, consumers may be willing to pay a premium for independence from possible future increases in the cost of conventional fuel. Alternately, consumers may accept this long-term cost differential as justified by the environmental impact of the solar car. Further research may be performed to determine what cost consumers will accept to maintain the environment in which they live.

COMPARISON TO CASE STUDY

The above approach to the design of an electrical system for a solar car follows a rigorous methodology of concurrent design, requirements traceability, and total life-cycle planning. Many projects are approached from a different perspective to achieve similar goals. Following is a comparison with a case example of preliminary design for an electrical system comparable to this project.

The case example is taken from the author's personal experience in the design and development of an electrical system for a prototype solar car. The case involves a national design competition, sponsored by General Motors, which invited various institutions to design, build, and race a solar car. The race took place along typical roads in the United States, from Florida to Michigan. The author was a major participant in the entry from the University of Pennsylvania, which was one of the 32 entries selected to compete in the race.

The prototype car was bounded by similar mechanical constraints to those described above, yet the systems methodology was not employed during the project. In fact, no formal methodology was specified for the project until, as described below, the system was partitioned into physical elements. This decision was not based on a specific methodology, but rather driven by a desire to "divide and conquer" the task at hand. Only after the project was completed was any attention given to the approach which had been incorporated.

The design of the case example started not from formalized requirements, but rather from the technical implementation constraints of the system. An analysis was performed to determine that the limiting factors were weight of the storage system, which was defined by the mechanical system, and the power produced by the solar panel. It was determined for this case that the power from the panel was sufficient to supply a 7.5 kW motor, which was obtained upon this determination. No analysis was performed at the time to determine the mechanical implications of this decision, nor its impact on the overall system. It was later determined that this motor was at least twice as powerful as required for the application.

The case project team was then organized by physical, not functional, areas to work on issues specific to each physical subsystem. Any interfaces between the physical subsystems were negotiated between the affected subteams. The design and development were intermingled, much like the process of functional analysis feeding back on the functional flow from the requirements. Any physical subsystem was analyzed for its primary function, which was developed immediately. From the implementation of the primary function, the supplemental supporting functions were designed and developed. In this respect, the case project obtained a set of derived requirements from the bottom up, rather than from the top down.

Given this fundamental difference in design methodology between the above analysis and the case example, an extreme divergence in products is expected. However, the final state of the electrical system produced in the case example fits relatively easily into the preliminary design from the above analysis.

Although there are a large number of minor differences in functional and physical architecture, fairly few major contrasts exist. One of these notable contrasts is in the selection of analog circuitry for the case example versus digital circuitry for the above analysis. This decision was directly related to the methodology used in design. Basically, the systems approach forces a system level view of the issue, which allows the design to account for the large number of applications for the digital processor throughout the various subsystems. When the subsystems are partitioned by physical boundaries, the problem is viewed more locally. In the course of the case study, it was never justified to employ a digital processor to solve any specific subsystem level problem. Discrete analog calculations were selected exclusively, because the design and development overhead of a digital processor outweighed its potential benefits.

Another specific difference in the case study was the redundancy optimization. The case design was based on an intuitive, rather than calculated, reliability model. Specifically, the configuration used 12 solar panel components, as opposed to the 4 as designed above. This caused an additional loss of 200 W of power from the panel for relatively little increase in reliability.

The systems approach inherently does not allow such subsystem level considerations as described above to outweigh system level analysis. The overhead is shared among subsystems to allow the benefits to be clearly realized for the system.

A final observation concerning the systems approach is noteworthy. Although the case example process was practically undefined at the time, the case methodology closely approximated, albeit from a vastly different perspective, the rigor of the systems approach. While inefficient decisions were made, the overall system produced was inherently similar to that conceived from the systems approach. One might rationalize that the systems approach does not provide significant value added. However, it is the author's conclusion that the systems approach is a formalization of a relatively intuitive process.

REFERENCES

1. Ayres, R.U. and R.P. McKenna, Alternatives to the Internal Combution Engine. Baltimore, MD: Johns Hopkins Press, 1972.

2. Blanchard, B.S. and W.J. Fabrycky, Systems Engineering and Anaysis. Englewood Cliffs, NJ: Prentice-Hall 1990.

3. Briggs, C., "Confronting the Future." *Powered by the Sun*, 1 November, 1987: 8ff.

4. Cooper, W.D. and A.D. Helfrick, Electronic Instrumentation and Measurement Techniques. Englewood Cliffs, NJ: Prentice-Hall, 1985.

5. Engel, J.F., R.D. Blackwell, and P.W. Miniard, Consumer Behavior. Orlando, FL: The Dryden Press, 1990.

6. General Motors Corporation, GM SunRayce USA. Miscellaneous literature, July 1990.

7. Lubulwa, A.S., Mechanisms of Car Choice. Aldershot, England: Avebury Press, 1989.

8. Organisation for Economic Co-Operation and Development, The Urban Electric Vehicle. Paris: OECD Press, 1992.

9. Sedra, A.S. and K.C. Smith, Microelectronic Circuits. New York: CBS College Publishing, 1987.

10. Streetman, B.G., Solid State Electronic Devices. Englewood Cliffs, NJ: Prentice-Hall, 1980.

11. Wolf, S., Guide to Electronic Measurements and Laboratory Practice. Englewood Cliffs, NJ: Prentice-Hall, 1983.

12. Woodson, H.H. and J.R. Melcher, Electromechanical Dynamics. New York: John Wiley & Sons, 1968.