On Improving Endurance of Unmanned Ground Vehicles: The ATRV-Jr Case Study

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***Abstract* – Unmanned ground vehicles (UGVs) have strict payload limitations, limited free space affecting power supply availability (number of batteries, size and volume) that impact on-board available energy resulting in limited endurance and operational range. This limitation is exacerbated by the addition of extra sensors and other related equipment needed for diverse applications. The ATRV-Jr UGV is considered as a testbed to identify causes of reduced runtime and operational range offering a detailed analysis of component power consumption. A comparative study between Lead Acid, Lithium and Fuel Cell technologies allows for power supply enhancement via i) an optimum design with weight, volume, runtime and re-chargeability being major restrictions and concerns, and, ii) the use of lower power sensors and processors without affecting vehicle functionality and operability.**

I. Introduction

Current UGV power sources are almost exclusively re-chargeable *lead-acid* and *NiCad* batteries due to the fact that both technologies are mature and well understood, as well as cheaper compared to more recent technologies such as *lithium* batteries and *fuel cells*.

Recent concerns about energy and environmental problems and advances in material and manufacturing engineering, have enabled a wider commercial product selection in *lithium* batteries and *fuel cells*. For example, *Proton Exchange Membrane Fuel Cells (PEMFC)* have already been tested and used in Autonomous Underwater Vehicles (AUVs) [1]-[4] and mobile robots [5], [6]. As stated in [4], *Direct Methanol Fuel Cells (DMFC)* is a better choice for mobile robots, but wide power range units are commercially unavailable.

UGV power requirements are mostly determined by the manufacturer for a specific vehicle configuration, ignoring the impact of possible upgrades, 'off-the-self' add on sensors and other custom made accessories, such as multiple cameras, Inertial Measurement Unit (IMU), GPS, compass, laser rangefinders and sonar sensors in addition to computer controlled processors and cooling fans.

Given that a UGV has limited power availability, endurance and range are drastically affected by the on-board sensor suite and other peripherals. This dependence and restriction becomes even worse if and when the UGV needs serve as the 'base station' and take off/landing platform for small/miniature unmanned electrical vertical take off and landing (VTOL) vehicles that require recharging upon landing on the UGV to continue their mission.

Considering restrictions and limitations on runtime and endurance as a function of a custom made vehicle and take off/landing platform (UGV-VTOL vehicle system), this paper provides a comparative study of currently available battery and fuel cell technologies (with respect to their application on UGVs), followed by a justified recommendation to improve UGV endurance and runtime based on a priori set mission requirements. Recommendations for power supply include energy requirements for the aforementioned landing platform as well (although details are offered in a separate paper) [7].

It is true that for most UGV outdoors applications, payload needs, sensor suite utilization and energy requirements are a-priori unpredictable. This makes proper sizing of energy storage devices a rather difficult task. However, for this research, considering trade-offs, as well as a wide range of outdoors applications related to search and rescue, surveillance, mapping, demining threat identification and patrolling, requirements for energy storage devices have been sized for a maximum travel distance of 25Km, 12 hours of continuous operation and two recharges of the electric unmanned VTOL. Since improved endurance is of high priority set requirements are coupled with recommendations for more efficient sensors.

II. Battery and Fuel Cell State of the Art

State of the art battery technology profiles are summarized in Table I, with *nickel cadmium (NiCad)* being the oldest technology. Its high life cycle, low internal resistance, and high load current characteristics make it an attractive choice for power tools, two way radios and biomedical instruments. Reusable *alkaline* batteries on the other hand are very cheap, but their high internal resistance limits their use to only very low current applications. Furthermore, despite low energy density, low price makes *sealed lead acid (SLA)* batteries attractive for applications where volume and weight is not a problem. *Lithium ion* batteries are the most expensive. With high energy density and cell voltage, lithium technology is an attractive choice for electronic devices where dimensions and weight are critical, such as consumer electronics. Furthermore, material technology advancements have enabled manufacturing of scaled up lithium batteries for satellite and

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electric vehicle applications as shown in Table II.

TABLE I
BATTERY TECHNOLOGY PROFILE (FROM [8], [9])

	NiCad	**NiMH**	**SLA**	**Li-Ion**	**Reusable Alkaline**
Energy Density (Wh/Kg)	40-60	60-80	30	100	80 (initial)
Internal Resistance (mΩ)	100-300	200-800	<100	300-500	200-2000
Cycle Life	1500	500	200-300	500-1000	10000
Cell Voltage (V)	1.2	1.2	2	3.6	1.5
Load Current	>2C	0.5-1C	0.2C	1C	0.2C
Operating Temperature (^{o}C)	-40 to +60	-20 to +60	-20 to +60	-20 to +60	0 to 65
Cost (USD)	$50	$70	$25	$100	$5
In Commercial Use Since	1950	1990	1970	1991	1992

TABLE II
LITHIUM ION FOR ELECTRIC VEHICLE APPLICATIONS (FROM [14])

Model	**Rated Capacity (Ah)**	**Nominal Voltage (V)**	**Dimensions (mm) W – L – H**			**Weight (Kg)**
LIM40-3	40	11.4	180	227	160	9
LIM40-7	40	26.6	180	451	160	17
LIM80-4	80	15.2	180	463	160	18
LIM80-7	80	26.6	180	766	160	30

Secondary batteries have limited runtime that is directly proportional to energy density and inversely proportional to load characteristics, with recharging process requiring several hours. On the other hand, *fuel cells* shown in Table III may provide constant power for as long as oxygen and hydrogen are provided, with refueling requiring only a few minutes. However, hydrogen storage [15] is a complex process, and the hydrogen container is bulky. Finally fuel cells have high operating temperatures.

TABLE III
FUEL CELL TECHNOLOGY PROFILE (FROM [16])

	PAFC	**AFC**	**MCFC**	**SOFC**	**SPFC**	**DMFC**
Operating Temperature (^{o}C)	150-210	60-100	600-700	900-1000	50-100	50-100
Power Density (W/cm2)	0.2-0.25	0.2-0.3	0.1-0.2	0.24-0.3	0.35-0.6	0.04-0.23
Projected Life (hrs)	40,000	10,000	40,000	40,000	40,000	10,000
Projected cost (US$/KW)	1000	200	1000	1500	200	200

Batteries and fuel cells have limited power densities that limit fast response to a demand greater than average load power demands. This power quality problem may cause the computer to reset and motors to stall. A common solution to this problem is to oversize the battery at the expense of cost, weight and size. Unlike batteries and fuel cells, super capacitors (Table IV at the end of the paper) have very high power but very low energy densities that limit their use as a primary power source. However, a high energy density device (battery) may be connected in parallel to a high power device (super capacitor) to form a *hybrid* power supply combination. Research reported in [10], [11] and [17]-[19] has shown that a hybrid configuration is a more effective solution than over sizing a battery.

III. CURRENT ATRV-JR ENDURANCE

Based on manufacturer specifications the *ATRV-Jr* is 0.62m wide, 0.77m long, 0.55m high, it weighs 50Kg and has a payload capability of 25Kg. It is powered by two 12 volt lead-acid batteries, 360 Watt-hours (720W-hr total), 12Kg (27lbs) and 343 inch^3 (4dm^3) each, connected in series. Runtime is terrain dependent and it is limited between 3-5 hours. However, due to custom modifications made to the vehicle under consideration (on-board computer platform and installation of additional external sensors for a wider range of applications) actual runtime has been reduced to about 1 hour!

Figure 1: Photo of the ATRV-Jr.

Without upgrades and added sensors, only the computer and vehicle motors are connected directly to the batteries. The Pentium 3 800MHz computer with 30W power demand at 24V requires 1.25A, whereas the two motors require 5.44A total (2.72A each). At load current of 6.69A, runtime is approximately 4 hours. Terrain dependency, smaller loads like cooling fans and 17 sonar sensors and losses result in runtime variation between 3 and 5 hours.

With upgrades and added sensors, 2 DC/DC converters and a 300W ATX power supply are connected directly to the batteries to provide regulated voltages to power the sensors and the on-board computer (see Figure 2). Theoretically, the total converter power of 230.28W at 24V requires 9.6A, whereas the 300W ATX power supply at 24V requires 12.5A. At full load with all upgrades the load current would be 28A, and runtime would be decreased to 1.1 hours. However, a more analytical analysis shows that the Pentium 4, 3GHz processor requires 120W. Considering 60-70% ATX power supply efficiency (built for desktops), the computer power consumption is about 156-162W. Furthermore, the total sensor power demand is only 86W and could be raised to 100W when considering 80% efficiency for the DC/DC converters and voltage regulators. This analysis gives a full load current of 17A and runtime of 1.8 hours. All runtimes are calculated based on advertised 30 AH battery capacity.

Further detailed analysis has shown that currently the *ATRV-Jr* is powered by two 12V lead-acid batteries with 33AH capacity at 20 hour discharge rate. To meet the 24V operating voltage, the batteries are connected in series. Figure 3 illustrates the performance of the DCS-33H lead acid battery pack. At 20 hour discharge rate and discharge current of 1.65A, the battery pack has a capacity of 33AH, whereas at one hour discharge rate and current of 19.7A the capacity drops to 19.7AH. Therefore, for a load current of 17A, discharge time is estimated at 1.2 hours and battery pack capacity is estimated at 20.4AH. Discharge current follows a linear relationship with capacity of the order $y=33.8-0.78x$ and an exponential relationship with discharge time or runtime of the order $y=27.86(e^{-0.21x})$, see Figure 3. Therefore, reduced endurance performance of the *ATRV-Jr* under consideration was expected since load demand increased and as a result battery pack capacity and runtime decreased.

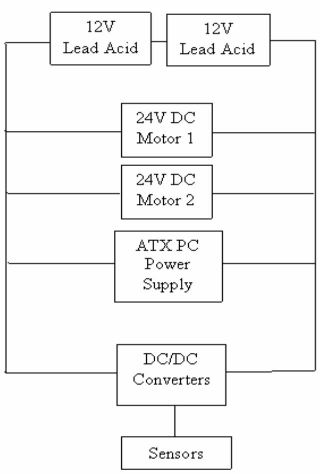

Figure 2: Connections of the ATRV-Jr. Subsystems

The next section describes how the ATRV-Jr endurance may be enhanced even after designing and installing a take off/landing platform on top of it.

IV. UGV WITH TAKE OFF/LANDING PLATFORM LOWER POWER DEMAND, HIGHER EFFICIENCY & ENDURANCE

As previously stated, requirements for energy storage devices have been sized for a maximum travel distance of 25Km, 12 hours of continuous operation and two recharges of the electric unmanned VTOL.

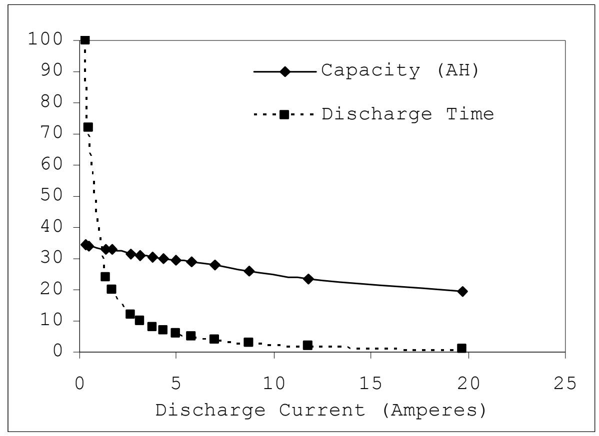

Figure 3: Capacity (AH) and Discharge Time (Hours) Versus Discharge Current of Deep Cycle DCS-33H Lead Acid Batteries.

Sensors & Processing platform

The current configuration of the *ATRV-Jr* with all sensors and power consumption requirements is presented in Table V. The cameras alone consume up to 60W out of the total consumption that is about 86W!

As a first step to save energy, lower power sensors that offer the same capabilities with the existing ones are proposed as shown in Table VI, resulting in a significant reduction of power consumption that is about 75% corresponding to total power consumption of 21.9W!

TABLE V
ATRV-JR CURRENT SENSORS

Sensor Type	Voltage (V)	Power (W)
Laser	24	17.5
Fans (two)	24	4.08
IMU	12	3
Fan	12	0.24
Sony Cameras (two)	12	60
GPS	9	0.6
Compass	5.1	0.1
Total Consumption		85.52

TABLE VI
PROPOSED LOW POWER SENSORS

Sensor Type	Power (W)
Sony CCTV Camera – FCB (2)	3.6
GPS-Carmin 18, 12 channel	0.3
IMU – ETB	0.5
Range Finder – SICK LMS-200-30106	17.5
Total Consumption	**21.9**

TABLE VII
PROCESSOR POWER CONSUMPTION (FROM [20]-[22])

Processor Type	Power Demand (Watts)	
	Idle State	Max Work Load
Intel Pentium D 820	50	134.3
Intel Pentium 4	49	130.6
Intel Pentium M	20.8 at 1.2GHz	30 at 2.66GHz
Intel Pentium 0.13 µm	30 at 1.6GHz	76 at 3.2GHz
Intel Pentium 90nm	30 at 1.866GHz	88 at 3.33GHz
AMD Athlon64, +3500	11.6	45.6

As a second step, a comparative study of processor power consumption (for processors with 3 GHz clock speed) shown in Table VII has revealed that the Pentium 4 processor with 3GHz clock speed consumes as much power as the two motors of the *ATRV-Jr*.

As observed in Table VII, the two Intel processors tested at 3 to 3.4GHz for maximum work load required power consumption of 131W and 134W respectively [20]. At idle state, Intel's speed step technology reduces the power consumption to 50W by running the processor at 2.865GHz. On the other hand the AMD processor at the same clock speeds consumes only 45.6W under load and 11.6W in idle mode. Furthermore, the Pentium M processor, specifically designed for mobile applications, has a maximum power consumption of 30W at 2.66GHz clock speed, whereas at idle state the demand drops to 21W by reducing the clock speed to 1.2GHz.

The recommendation is to use a Pentium M 2.66 GHz and Compact Flash memory for storage. Compact Flash memory has the advantage of low power consumption, vibration resistance and plug in plug out capability. The latter feature makes programming of the *ATRV-Jr* easier and allows for storage of various mission scenarios in different memory modules, loading them as needed.

With the proposed configuration, maximum power demand of the processor including that of the proposed sensors is about 60W. It is also proposed to use the MI-ATX power supply with 80-90% efficiency (as opposed to the currently used desktop power supply with 60-70% efficiency), thus reducing the total estimated power consumption from 300W to 70W only.

In summary, following the stated recommendation for low power sensors, processor and power supply, results in decreasing the total full load power demand (including the motors), by 44.6% (from 408W to 226W) and as a consequence runtime increases from 1.1 to 2.5 hours.

Powering the ATRV-JR with lithium batteries

The *ATRV-Jr* speed is 1m/s that is translated to 3.6 Km/hr. The additional load of the take off/landing platform on top of the UGV has an accurately estimated power consumption of 25W and VTOL recharging need of 200Wh. Total required energy to achieve the set goal is estimated to be 1957Wh resulting in a required battery capacity of 85Ah.

Comparing available energy storage devices as shown in Tables I to IV, it is observed that scaled up lithium technology batteries require 1/3 the weight and ½ the volume of lead acid batteries [8], [9], [23] and [24]. Therefore, for the same available volume, lithium batteries double the runtime and reduce weight from 24 to 8Kg. By comparing lead acid and Li-Ion batteries in Table VIII (shown at the end of the paper), it is seen that *Li-Ion* VL45E cells produced by Saft provide 3 times the energy density of lead acid batteries. Furthermore, the use of the high energy cells VL45E and VL27M instead of the high power cells VL30P and VL20P, provide the total mission energy demand with approximately one third less weight and volume. For 10 hour continuous operation, use of VL45E cells requires a matrix of 14 cells at a weight of 15Kg, whereas the use of the VL30P cells requires a matrix of 21 cells at a weight of 23.1Kg.

Alternative designs based only on lithium technology batteries, as shown in Table VIII, may reduce the battery pack weight to 15Kg and still achieve a runtime of 10 hours. However, lithium batteries may not be the best available choice; current commercial scale up lithium batteries require at least 2 to 3 hours to be charged. For this reason fuel cells offer a better choice for powering the *ATRV*, due to their easy refueling process. This recommendation is justifiable since as stated in [1] the Urashima AUV had an increase in travel distance of 65.4% when powered by a fuel cell system instead of lithium ion batteries.

Using a combination of lithium batteries and a fuel cell

DMFC (Direct Methanol Fuel Cell) has a relatively low operating temperature of 120^{o}C compared to other FC systems, making it the best and safest choice. However, commercially available DMFC such as the 250W iGen system provided by Idatech does not meet the required power demand. As such, based on commercial availability, the next best choice is the PEMFC (Proton Exchange Membrane Fuel Cell).

Two other available options are the Ballard's Nexa [25] and Hydrogenic's H2X-82 [26] stacks, with weight and volume of 13Kg, 46.2dm^3 and 7Kg, 5.8dm^3, respectively. But both are not suitable because of weight and volume restrictions; the dimensions and weight listed are for the stacks only. The complete system including the hydrogen storage tank, air compressor and valves is too big and heavy for the *ATRV-Jr*.

TABLE IX
ALTERNATIVE SOLUTION (DMFC AND BATTERY).

Type	iGen DMFC by Idatech	Li-Ion VL45E Cells, 7x1 matrix, by Saft	Total Performance
Capacity (Ah)	125	45	170
Voltage (V)	24	25.2	24
Weight (Kg)	Unit 9.00Kg Fuel 5.54Kg	7.49	23.03
Total Energy (Wh)	3,000	1,134	4,134
Specific Energy (Wh/Kg)	206.33	151.4	179.38
Energy Density (Wh/ dm^3)	105	313	105
Specific Power (W/Kg)	17.19	664	237.1
Power density (W/dm^3)	8.75	1392	133
Total Runtime (hr)	-	-	18.3

An alternative solution is the 250W DMFC by Idatech together with Li-Ion cells by Saft. Even though the available energy from the DMFC is directly proportional to the amount of fuel, its power limitations require the use of a second parallel energy storage unit. The proposed fuel cell and battery design, shown in Table IX, has the same weight as the proposed design of Table VIII and 21% higher runtime.

Finally, the high energy density DMFC and high power density Li-Ion design can be classified as a hybrid system similar to battery and super-capacitor hybrid systems. An active hybrid system would be proposed instead of a passive hybrid system. The introduction of a control system, DC/DC converter [27], eliminates all the negative effects of a passive hybrid system and gives more design flexibility. Furthermore, reference [28] has shown that a multilevel DC/DC converter can provide optimum fuel cell utilization.

V. Further Design Considerations

Several designs have been investigated including Lead Acid, Lithium and Fuel Cell Technologies. Lead Acid is the cheapest technology at a cost of approximately $320 per KWh, the proposed Lithium technology from Saft, costs $2500 per KWh whereas the proposed hybrid systems currently costs $3,104 per KWh and is estimated to drop to $1893 per KWh since the Idatech fuel cell is estimated to drop form $10,000 to $5,000 by the end of this year. The hybrid system is newer and as a result more expensive but at the same time it provides easy refueling and meets the power requirements without the need to over-size the batteries. Worth noting is that the projected cost for DMFC will drop to $200 per KW [16] in which case the proposed hybrid design should drop to $696 per KWh.

Additionally, when choosing any battery technology, care should be taken on operating temperatures and discharge currents. For choosing off the shelf products it is very important to identify the discharge rate and current of indicated capacity. An indicated capacity of 30AH at 20 hours discharge rate has a discharge current of only 1.5A, whereas for the same cell or battery pack, an increase of discharge current drops the capacity exponentially. As presented in figure 3 for the specific lead acid pack, discharge current follows a linear relationship with capacity of the order $y=33.8-0.78x$ and an exponential relationship with discharge time or runtime of the order $y=27.86(e^{-0.21x})$.

VI. Conclusions

This paper examined and identified reasons for the reduced UGV endurance, and in particular of a custom made *ATRV-Jr*. As presented, the reasons were not only lead acid batteries but also excessive power demand that exponentially decreased the battery discharge time. Initial experimental analysis with comparative data suggested that for longer runtimes, it is first recommended to use lower power and more efficient sensors rather than over sizing the battery packs. Low power sensors, a Pentium mobile processor and a 90% efficient power supply may decrease power consumption by 45%. It has been shown that lithium ion technology meets the set energy requirements of 25Km/12hr goal with only 15Kg whereas lead acid technology would require more than 72Kg. Use of high energy cells such as VL45E and VL27M would provide the total mission energy demand with approximately one third less weight and volume. On the other hand, a combination of a DMFC and Li-Ion has an energy density of 105Wh/dm^3 and offers runtime of 18.3hrs. The proposed DMFC and Li-Ion solution offers a refueling time of just a few minutes whereas Li-Ion batteries alone need several hours. Therefore, for outdoor applications such as search and rescue, DMFC combined with Li-Ion cells are the most suitable design considering refueling time, weight, volume and runtime.

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TABLE IV

SUPER-CAPACITOR TECHNOLOGY PROFILE (FROM [10] - [13])

Brand	Voltage	Capacitance	ESR (mΩ)		Energy	Power	Weight	RC time constant
	Volt	Farads	DC	AC	Wh/Kg	W/Kg	Gr.	Sec
Single Cell								
EPCOS	2.5	1800	0.6	0.3	2.9	2300	540	1.08
NESS	2.3	20	55	40	3.7	6600	4	1.10
Maxwell	2.7	2600	0.4	0.28	5.6	10400	470	1.04
Skeleton	3	47	5.5	-	11.5	9600	5	0.26
MODULES								
EPCOS	14	200	5	2.6	1.9	1700	2800	2.50
EPCOS	42	67	15	8	2	1700	8200	1.01
NESS	5.4	1.5	200	150	1.74	10410	3.5	0.30
Maxwell	16.2	430	3.5	2.5	3.1	5200	5000	1.51

TABLE VIII

COMPARISON OF LEAD ACID AND LI-ION BATTERY COMBINATIONS

	Current	Alternatives			
Type	**DCS-33 Lead Acid**	**Li-Ion VL20P Cells, 7x4 matrix, by Saft**	**Li-Ion VL27M Cells, 7x3 matrix, by Saft**	**Li-Ion VL30P Cells, 7x3 matrix, by Saft**	**Li-Ion VL45E Cells, 7x2 matrix, by Saft**
Capacity (Ah)	26 at C/3	80 at 1C	81 at C/3	90 at 1C	90 at C/3
Voltage (V)	24	25.2	25.2	25.2	25.2
Weight (Kg)	24	22.4	16.17	23.1	15
Total Energy (Wh)	624	2016	2041	2268	2268
Specific Energy (Wh/Kg)	26	90	126.23	98.2	151.4
Energy Density (Wh/ dm^3)	78.6	187	252	209	313
Specific Power (W/Kg)	208	1413	987	1136	664
Power Density (W/ dm^3)	604	2974	2000	2451	1392
Total Runtime (Hrs)	2.7	8.92	9.03	10.0	10.0