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On the Feasibility of using Servo-Mechanisms in Wireless Multimedia Sensor Network Deployments

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***Abstract*—This paper considers the use of servo-mechanisms as part of a tightly integrated homogeneous Wireless Multimedia Sensor Network (WMSN). We describe the design of our second generation WMSN node platform, which has increased image resolution, in-built audio sensors, PIR sensors, and servo-mechanisms. These devices have a wide disparity in their energy consumption and in the information quality they return. As a result, we propose a framework that establishes a hierarchy of devices (sensors and actuators) within the node and uses frequent sampling of cheaper devices to trigger the activation of more energy-hungry devices. Within this framework, we consider the suitability of servos for WMSNs by examining the functional characteristics and by measuring the energy consumption of 2 analog and 2 digital servos, in order to determine their impact on overall node energy cost. We also implement a simple version of our hierarchical sampling framework to evaluate the energy consumption of servos relative to other node components. The evaluation results show that: (1) the energy consumption of servos is small relative to audio/image signal processing energy cost in WMSN nodes; (2) digital servos do not necessarily consume as much energy as is currently believed; and (3) the energy cost per degree panning is lower for larger panning angles.**

I. Introduction

Wireless sensor networks are rapidly evolving from their early roles as networks returning simple scalar measurements into a wide variety of new applications requiring the processing of more complex signals such as audio or video. Given the resource and bandwidth constraints frequently present within sensor networks, new research questions are emerging for processing and delivery of this audio and video information within the network, such as: whether or not to transmit raw data to more capable nodes within a hierarchical topology for further processing, or whether to carry out in-network processing and aggregation to filter out the most relevant data.

We refer to sensor network applications that include audio and video sensors as Wireless Multi-media Sensor Networks (WMSNs). Two target application areas for WMSNs are environmental monitoring and ad hoc surveillance. In the former, a network of wireless multi-media nodes monitors wild-life habitats, rare species in remote locations, and phenology[1] without any human disturbance. For ad hoc surveillance the multi-media sensors are useful for disaster management scenarios such as forest fires and floods. In both of these settings, pre-existing infrastructure may be unavailable and/or destroyed and a wireless battery/solar powered deployment is necessary.

[1]This is the study of periodic biological phenomena.

This paper describes the design and development of our second generation WMSN node platform, which includes passive infrared (PIR), audio, and image sensors, a Blackfin DSP board, a 16 GB micro-SD card, and a panning servo mechanism. The energy cost of operating the devices onboard this platform vary widely by scale and information benefit. The PIR sensor has low energy cost to sample but provides a low level of information, while capturing an image after panning the camera, using the servo, towards the event of interest can hold sizable information content, albeit at a high energy cost. Because of this disparity among devices within WMSN nodes, we propose a novel intra-node hierarchical framework for managing these devices and combining the multi-modal signals they produce. Inspired by the low power listening [1] concept, the framework establishes a hierarchy of devices (sensors and actuators) within the node and uses frequent sampling of cheaper devices to trigger the activation of more energy-hungry devices - a concept we demonstrated in [2] for audio-triggered image capture.

Within this framework, the main focus in this paper is to establish the utility of a servo-mechanism in WMSNs to provide sensors with panning ability for enlarging their coverage area. While it is possible to use off-the-shelf Pan-Tilt-Zoom (PTZ) cameras, we are more interested in a servo mechanism that can be easily integrated with many different types of systems. As an actuation mechanism, the energy consumption of the servo is an important factor to consider and weigh against the benefit of panning towards events of interest to capture higher quality images. Although much work has been done on PTZ devices for large non-power constrained systems [3] [4], their applicability for resource-constrained WMSNs has only been described analytically and qualitatively [5], with little consideration of their energy implications and feasibility. To the best of our knowledge, no implementation or evaluation work has been done on WMSNs with servo mechanisms.

This paper considers 4 digital and 4 analog servos for measuring and comparing their energy consumption profile. Our energy measurements indicate that, contrary to popular belief, digital servos are comparable to analog servos in terms of energy consumption and in some cases consume *less* energy[2] due their increased angular velocity. We also determine that the energy cost per degree of panning reduces for larger panning angles as servos reach steady state motion. Based on a simple implementation of our hierarchical duty cycling framework, we conclude that servos are an appropriate fit for WMSNs, as their energy consumption is small relative to the DSP energy consumption in WMSN nodes, and is of the same order as radio energy consumption, when properly duty cycled.

The remainder of this paper is organised as follows. The next section gives an overview of current work on WMSNs. Section III then discusses the hierarchical sampling framework for WMSNs and our second generation WMSN platform, along with the target applications. Section IV then analyses the energy consumption of the different servos and shows how they compare with other system resources. Finally, section V discusses the results and concludes the paper.

II. Related Work

This section discusses related work on two main aspects of WMSNs separately: multimedia node designs and wide angle imaging.

A. Multi-media node designs

A number of interesting multi-media node/network designs have occurred over the past number of years in WMSNs. The Cyclops camera [6] is one of the earliest designs and uses a combination of a microntroller unit (ATMEL Atmega128L) with a Complex Programmable Logic Device (CPLD). The image sensor used is a CIF resolution (352 × 288 pixels) CMOS camera module (ADCM-1700) from Agilent Technology. The node itself has 64kB of off-chip RAM and 512kB of flash memory, and an interface to a Mica mote. Its significant limitations are the small amount of memory, and the limited address space and computational ability of its processor.

The Mesheye mote developed by Stanford University has a unique vision system: a low-resolution stereo vision system (30x30 pixels, 6-grayscale) continuously determines position, range, and size of moving objects entering its field of view. The stereo vision system monitors the environment and wakes up the mote, upon detection of an event, for more sophisticated processing of images captured by another CMOS camera (640x480 resolution). All processing load is handled by the AT91SAM7S microcontroller running at 47.92MHz clock rate. Our system uses a similar approach but uses a separate PIR sensor instead. However, the Omnivision CMOS image sensors used within our WMSN node also provides for low and high resolution images, enabling an integrated detection/recognition system.

The CITRIC camera node [7] uses a frequency scalable, fixed point, CPU (up to 624MHz), 16MB FLASH and 64MB SDRAM. The image sensor used is the Omnivision OV9655 [8]. The motes are designed to do some basic in-network processing procedures returning only results obtained (such as a bounding box of the detected image) over the radio. While this system resembles ours in terms of processor speed, amount of RAM, and in its aim towards an in-network processing approach to solve the energy efficiency problems [9], our system uses a more powerful, highly integrated, MCU/DSP Blackfin processor and PIR sensor for motion detection. Our microSD card is capable of up to 16GB of storage also.

Senseye [5] is a network architecture that uses three-tiers to achieve both low-latency and power efficiency at the same time[3]. This network is one of the first to propose PTZ cameras in a WMSN scenario. However, the device considered is a self contained high power device, in contrast with our WMSN node's integrative approach. While Senseye proposes an *inter-tier* approach for WMSNs, our work here proposes an *intra-tier* approach, where the hierarchy resides within the node itself, as the framework in Section III illustrates.

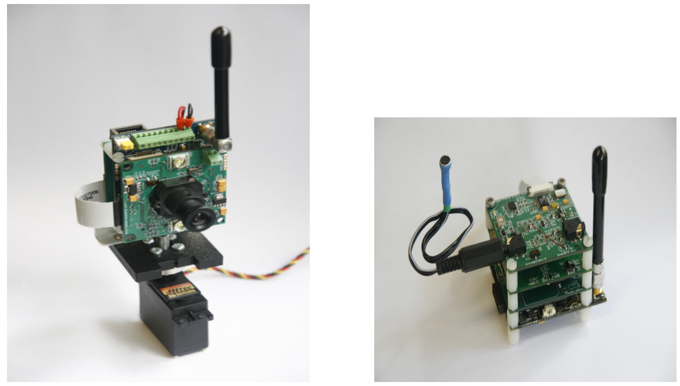
FireFly Mosaic [10], is a wireless sensor network image processing framework with operating system, networking, and image processing primitives that assist in the development of distributed vision-sensing tasks. It is of interest in the present context as it considers the use of 4 servo ports. However, the aim of these servo ports has been mainly for implementing robotic type applications as opposed to WMSNs.

B. Wide-angle imaging for WMSNs

A common drawback of the systems described above is that the coverage area of each individual sensor is often limited by the use of a narrow-angle lens, which provide perspective projections of the 3D world (e.g. the CITRIC system [7], [11]). Studies of coverage maximization problems rely on the assumption that a large number of nodes are densely deployed [12] and generally focus on distributed algorithms that maximize total area covered by limiting the amount of overlaps among camera nodes [13] or to maintain maximum angle coverage of a particular object of interest. In both cases, camera nodes must be able to overlap their FOV if required. While this offers a good solution to localization of nodes or objects in dense deployments, it may lead to insufficient information gain in sparsely deployed WMSN networks, where overlapping fields of view of cameras are simply not possible. To help overcome these problems, we consider the use of a servo-mechanism to offer additional degrees of freedom, allowing each individual sensor to form a semi-panoramic view of its surroundings. This enables each sensor to offer a much more immersive experience than a simple snapshot with a narrow field of view, thus creating greater opportunity of capturing an event of interest. Before considering the applicability of servos in section IV the next section discusses our first and second generation node designs along with a discussion of our proposed framework.

[2]When compared with analog servos of similar specifications.

[3]As a general definition a tier can be considered to be a level of operation within a hierarchical structure that, while returning less information, also consumes less energy.



(a) Camera Node. (b) Audio Node.

Fig. 1. Audio and Camera nodes.

III. System Description

A. Target Applications

We are particularly interested in image processing for low-power, low-bandwidth sensor networks for long-term outdoor deployments. For example, we are currently deploying a WSN at Springbrook, a former winery site. The purpose of the project is to track the restoration of biodiversity on this land, which will be used to enhance the knowledge of rainforest restoration and its effectiveness at recovering biodiversity. Currently there are 10 micro-climate nodes deployed monitoring temperature, humidity, leaf wetness, soil moisture, wind speed, and wind direction. The number of sensor nodes will increase to about 40 nodes by the beginning of next year, with up to 200 sensor nodes planned for 2.5 years time. Only a subset of these nodes will be multi-media nodes (approximately 20). The Springbrook plateau presents a unique opportunity to work on land which is being restored from agricultural grassland to native rainforest vegetations. Springbrook is listed as one of Queensland's five World Heritage areas. With its high rainfall environment and wide range of environmental gradients a unique opportunity exists for developing WMSNs, which can be used for species classification [14], for example.

Another application we are currently investigating with the WMSNs is an automated malaise trap. A malaise trap is a stationary flight trap for catching insects. Its purpose is to provide indices of absolute insect populations and to determine the direction of flight. Insects flying into the front of the trap are funnelled into the collecting vessel attached at the highest point, which is so placed as the insects tend to move towards light and away from gravity. The collecting vessel for our setup contains a wireless multi-media node at one end and a servo-motor at the other for insect release[4]. The node captures an image of any trapped insects which can be determined by the use of a PIR sensor or simple image differencing technique; the insects are released once the required image is obtained. Although the servo-mechanism is not used with the node itself, it still represents a source of energy consumption to the overall device and needs to considered in the energy budget for the system.

B. Current Node Architecture

With the applications above in mind, we have been developing a Wireless Multi-media Sensor Network for long term outdoor deployments. Figures 1(a) and 1(b) show our first generation camera and audio node, respectively. Each node uses a wireless mote and DSP for both communications and signal processing, respectively. The particular mote we use is known as the Fleck™-3B. The Fleck™platform is a robust family of motes designed at CSIRO for outdoor applications in environmental monitoring and agriculture.

The DSP is an Analog Devices 600MHz ADSP-BF537 Blackfin processor. This processor is, in-fact, a *convergent processor* - a device that tightly combines an MCU with a DSP in a single device. It is therefore not a DSP with an enhanced instruction set nor a microcontroller with DSP extensions but rather a combination of a high-performance media processor and compiler-friendly processor optimized for both control and signal-processing operations [15]. It operates as a 16-bit DSP and a 32-bit MCU simultaneously and supports DMA and cache memory controllers for improved efficiency. The implementation we use is the BlueTechnix CM-BF537E board which comprises the CPU with 132KB internal SRAM, 32MB external SDRAM and 4MB flash. In [7] it was shown that the processor on the CITRIC node, whilst performing a simple background subtraction function running at 520MHz, used about 970mW of power - allowing for approximately 16 Hours of continuous operation when using 2700mAh batteries. This is comparable to the Blackfin as was shown in [9].

The Camera Daughterboard contains the image sensor chip, lens holder and two switchable ultra-bright LEDs for illumination. The image sensor chip is an Omnivision OV7648, VGA or QVGA color CMOS image sensor with Bayer pattern filter that can capture images at a maximum rate of 30fps or 60fps respectively. The sensor is progressive scan and supports windowed and sub-sampled images. The camera parameters can be set by the DSP over the local TWI bus.

The current audio nodes use a 150MHz Texas Instruments TMS320F2812 Digital Signal Controller (DSC) to manage processing of digitised audio and storage of audio to a SD flash card. Audio acquisition is done by an Analog Devices AD73311 low power, 16-bit codec with internal programmable gain amplifier. A Panasonic WM-61A omnidirectional, high sensitivity electret capsule microphone captures sound, and a custom, fixed gain microphone preamplifier circuit amplifies the microphone output before it is input to the audio codec. We have used this platform for experiments in bird sound classification [14], and in two extended outdoors deployments to capture bird and frog vocalisations for subsequent offline analysis. The power consumption of our current audio nodes whilst acquiring audio, performing a simple processing task such as computing average energy, and storing the audio stream to an SD card is approximately 1.8W. The power

[4]This is to be preferred over current methods that rely on ethanol to kill the insects.

consumption is dominated by the TMS320F2812 DSC, which is an older processor not particularly suited for low power applications and one that lacks DMA (introducing significant processor overhead to manage storage of incoming audio samples).

C. Proposed Framework

To use the multi-media nodes in a real deployment we have chosen a specific topology, which we feel will be most effective in the long-term. Whether or not to use a single-tiered system or a multi-tiered system has been under some debate in the community. Benefits of a multi-tiered approach include low cost, high coverage, high functionality, and high reliability. It is shown in [5] that a multi-tier network can achieve low-latencies without sacrificing energy-efficiency.

However, another possible option is to use a homogenous network of moderately powerful devices and to operate them in such a way that they act as a multi-tier network. This idea is becoming increasingly feasible as single-chip devices have the ability to operate in multiple operating modes of varying powers and complexity. We envision this *intra-tier* approach to be the design of choice in future WMSNs for a number of reasons. It offers the benefits of a multi-tier approach but significantly reduces development time and communication costs between different tiers - the latter which will now be in the form of serial or SPI instead of wireless. In a heterogenous hierarchical network *inter-tier* interactions can increase the complexity of application design significantly [5]. Also, inter-tier wakeup is not only a challenging problem (as it is required that no wasteful wakeups are attempted) but can also consume a significant amount of energy at upper tiers. The separation of detection and recognition across multiple tiers introduces large amounts of latency which may be undesirable in a rare species detection application, for example. Also, the number of tiers is inherently quite small in this type of design, reducing system flexibility (unless a hybrid approach is taken). A homogenous design where the hierarchy is contained within each node reduces many of these problems. Figures 2 and 3 illustrate the ideas of moving from an inter-tier to an intra-tier approach. In the latter figure the size of each device reflects its relative power consumption (not to scale) with the servo using an unknown power consumption (dashed box) that is being answered in the present paper.

Our next generation of multi-media sensor nodes is currently in its advanced development stages. To help realise the above design goals our upgraded architecture integrates audio and video into a single device. It also improves upon the existing capabilities described above by providing an enhanced image sensor, a more capable and efficient audio codec, and a passive infra-red (PIR) sensor onto a single PCB. The Bluetechnix CM-BF537E module as used in the current camera node is retained in the new design. Due to the nature of the employed devices and their capability to operate in different power states we are considering the new design, in effect, as a hierarchical structure with multiple internal tiers as shown in figure 3. To leverage the benefits of such an architecture we are currently developing a framework which will allow efficient interaction of each tier within a device. As a simplistic illustrative example consider figure 4. In this example we can consider the interaction of the different components shown in figure 3. The lowest power sensor (PIR) is sampled the majority of the time and is used to assist a sensor of higher complexity and higher energy cost (e.g. Audio); this in turn can be used to assist upper tiers. Although the example shows a periodic triggering of each sensor in some relation to the sensors below it, in reality this will be random. We now describe the details of our next generation architecture which will clarify the benefits of such a framework.

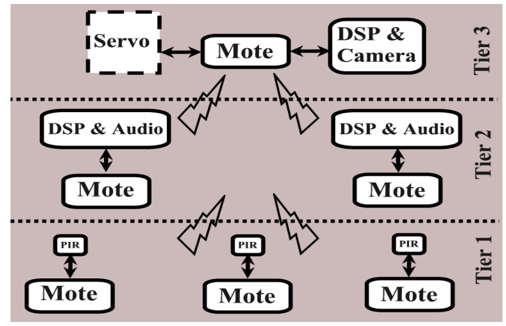


Fig. 2. System example with multiple separate tiers.

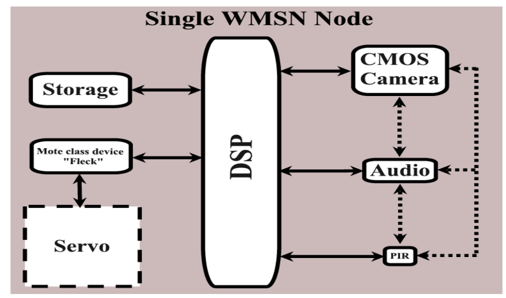


Fig. 3. Combining multiple tiers into one device. Component size represents its power consumption (not to scale).

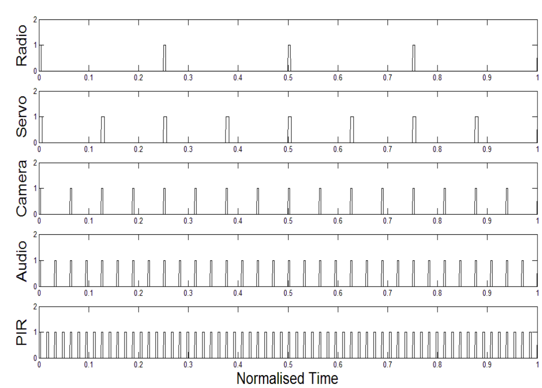


Fig. 4. Illustration of how each device interacts.

D. Upgraded Node Architecture

We are currently evaluating three new types of image-sensors: The OV9655 (as used in CITRIC), the OV9665 and the OV3642. The former two have very similar specifications: 1.3 MP, 1/4 inch sensor, full-frame, sub-sampled, scaled or windowed 8-bit/10-bit images in a wide range of formats. They offer a high data rate of up to 15 frames per second in SXGA resolution. The main advantages of the OV9665 are that it consumes 10mW less power that the OV9655 and offers more robust image detection processing on board. However, it has a very low sensitivity: 450mV/(Lux.sec) compared with 1.1V/Lux on the OV9655. Both chips support image sizes SXGA (1280x1024), VGA, CIF, and any size scaling down from CIF to 40x30, and provide 8-bit/10-bit images. The image array is capable of operating at up to 30 frames per second (fps) in VGA, CIF, and lower resolutions, and 15 fps in SXGA. The typical active power consumption is 90 mW for the OV9655 and 80mW for the OV9665 and the standby current is less than 20 mA in each.

The OV3642 is of superior quality in many respects to the OV9655/OV9665. To begin with it has a resolution of 3.1MP. However, it is possible to obtain any resolution down from this. It has an extremely useful feature referred to as TrueFocus ISP (Image Signal Processing). It also contains an anti-shake engine for image stabilisation - a beneficial feature for actuated nodes. The sensor contains an integrated JPEG compression engine. These advanced functions come at the cost of 300mW of power which, currently, is not feasible for WMSNs. However, with the appropriate use of this chip it may offer many benefits to future WMSNs. All of the CMOS imaging sensors described provide a large amount of flexibility adding to the benefits of the intra-tier hierarhical approach we are considering.

A Texas Instruments TLV320AIC3254 stereo audio codec will be used on the new multimedia node. The recently-released TLV320AIC3254 can sample at rates up to 192kHz, and consumes 6.1mW when sampling two channels of audio at 48kHz. A range of software-configurable processing blocks (e.g. IIR/FIR/Biquad filtering) can be applied to the input audio stream, and an internal DSP core allows additional customised processing. The balance between audio acquisition quality and power consumption can also be configured via software.

The Passive Infrared (PIR) sensor under evaluation is the Panasonic AMN1x111 where x $\in$ $\{1, 2, 3, 4\}$. These are digital, 5V, PIR sensors with each of the four types referred to as: "Standard detection", "Slight motion detection", "Spot detection" and "10m detection". The minituarised sensor has a built in amplifier and detects changes in the infrared radiation of the environment within its field of view due to movement by a person or object. For a small, compact PIR sensor this FOV can be 50 degrees in the azimuth and 40 degrees in the zenith. It consumes a mere 170μW of power (or 46μ W for the low power version).

Another addition to the intra-node hierarchy is the development of a daughterboard containing multiple radios. Although we are only considering low-power radios at the moment it is envisaged that we will include a higher speed, more capable radio (such as wi-fi) in the near future as lower power options become available. This will allow a truly homogenous system which has the ability of leveraging the framework described.

IV. Servo Mechanisms

Combined with the above capabilities, we are also considering the use of a servo-mechanism as another "tier" in our conceptual hierarchical structure. Considering the applications outlined in the previous sections, it is clear that servos have the potential to offer substantial benefits to a WMSN deployment. As a preliminary investigation into these benefits, we study the energy consumption characteristics of a number of servos available to us in order to help determine how they might fit into our framework. Both digital and analog servos are investigated. The digital servo uses a micro-controller to analyse the incoming signal and control the initial power to the servo-motor. Digital servos have reduced *deadband*, faster response, quicker and smoother acceleration, and better resolution and holding power. This would seem to preclude the use of analog servos; however, comparison of the datasheets suggest that analog servos consume less power than the digital variety for the same specifications, which further motivated our energy measurements of both servo types.

Servos contain a number of discrete blocks: a motor, a gear box, a positional sensor, an error amplifier, and a pulse-width to voltage converter. The control pulse is a Pulse-Width-Modulated (PWM) signal with a varying duty cycle. The standard period of the pulse is about 20ms and the pulse-width itself is from $900\mu s$ to 2.1ms giving a duty cycle from about 4.5% to about 10%. The rotational position of the sensor is determined by the positional sensor (a potentiometer, for example), which is fed back to an error amplifier. The error signal is then applied to the motor to correct its position.

Table I gives a rough comparison of each of the 8 servos we tested (although the majority were from Hi-Tec [17], other varieties are also available [18]). Most of the servos used offer a maximum of 180 degrees of rotation[5] with some offering only 120/160 degrees of rotation (Futaba servos) or a full 1260 degrees (HS-785HB).

For WMSNs it may be necessary to know the exact angle to turn for a given pulse-width. For instance, the simple localisation procedure used in [2] requires a deterministic relationship to exist between the pulse-width of the control signal and the angular displacement of the motor. A plot of this relationship for both a digital (HS-5645MG) and analog (HS-785HB) servo is shown in figure 5. The relationship in both cases is quite linear and therefore suitable for our application and other WMSN applications.

Servos are generally rated for both speed and torque. We consider servos with different levels of available torque as we

[5] Continuous rotation is possible but it requires removal of the positional sensor.

	Analog				Digital			
	HS-785HB	HS-311	Futaba S3004	HS-55	HS-5645MG	HS-5245MG	HS-5065MG	S3153
Speed (sec/60 degrees)	0.23	0.15	0.19	0.14	0.18	0.12	0.11	0.10
Current (idle, mA)	8.7	7.7	8	5.5	9.1	3	3	-
Current (operating without load, mA)	285	180	-	180	500	230	240	-
Maximum Torque (oz-in)	183	49	56.8	18.05	168	76	30.55	23.5
Dead-Band Width (μs)	8	5	-	8	8	1	2	-
Approximate Cost (US$)	40	9	14	14	55	48	47	35
Gear Type	Karbonite	Nylon	Nylon	Nylon	3 Metal, 1 Resin Metal	4 Metal, 1 Resin	Metal	Nylon

TABLE I
COMPARISON BETWEEN DIFFERENT SERVO TYPES AS SPECIFIED IN [16]. THE VALUES QUOTED ARE FOR AN OPERATING VOLTAGE OF 6.0 V. SOME VALUES FOR THE FUTABA SERVOS WERE NOT AVAILABLE.

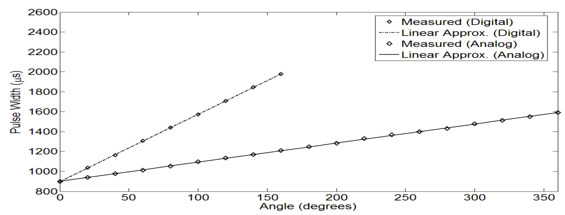


Fig. 5. Relationship between PWM pulse-width and the angle for our setup.

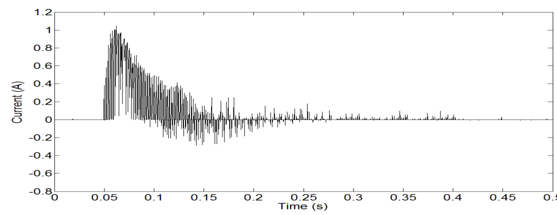


Fig. 6. Current consumption of HS-5645MG moving 20 degrees.

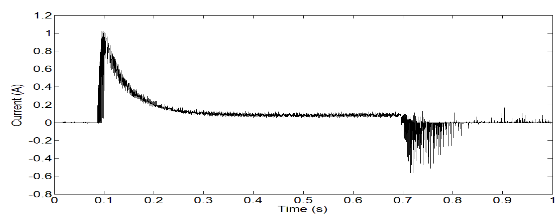


Fig. 7. Current consumption of HS-5645MG moving 180 degrees.

wish to encompass a range of different possible scenarios. Nodes that employ a tilt mechanism (which we can consider yet another tier in the conceptual hierarchy of the node) require a larger torque when compared with only a panning mechanism. It is possible, in a lot of cases, that two servos of the same type will be manufactured with one rated towards speed (sacrificing torque) and one rated towards torque (sacrificing speed). For a panning mechanism, speed may be of more importance[6]. However, for a tilt mechanism the opposite may be true. We therefore consider both types.

A. Energy Measurements

In order to determine the energy consumption of the servos in different scenarios, we place a 1 Ω resistor in series with the ground line of the device as it is turning. The voltage across this resistance is then measured on an oscilloscope - this value is equal to the current in the circuit. The voltage across the load is also measured, allowing calculation of the power and energy. This simple setup enables a real-time evaluation of the power consumption of each servo under different scenarios.

To determine the amount of energy used by each servo, they are configured to rotate in 20 degree increments up to 180 degrees. The resulting waveforms are obtained during this time. We perform the tests both with the camera-board attached and without. Due to the light weight of the camera-board (≈ 100g) the difference between the two is negligible. Plots of the actual waveforms are shown in figures 6 and 7 for a digital servo (HS-5645MG), in figures 8 and 9 for one analog servo (HS-785HB), and in figures 10 and 11 for the other analog servo (Futaba S3004). The analog and digital waveforms look remarkably different. In all three cases, there is an initial large current draw beyond 1A as the servo turns on. This current quickly reduces as the servo reaches steady state - as is clear from figures 7, 9, and 11. As the servo reaches its set-point, there is a large pulsing current draw from both analog servos and a small back-current from the digital servo. The pulsing current draw of the S3004 is especially high, most likely because the large angular velocity of this servo requires large current pulses to quickly reduce its velocity to zero upon

[6]Our current camera node (cf. figure 1(a)) weighs a mere 100g (3.5 oz) and the degree of torque required for panning is quite small. This will be similar with the upgraded node.

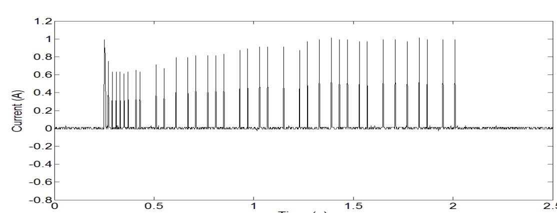


Fig. 8. Current consumption of HS-785HB moving 20 degrees.

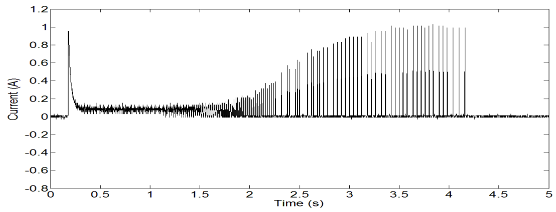


Fig. 9. Current consumption of HS-785HB moving 180 degrees.

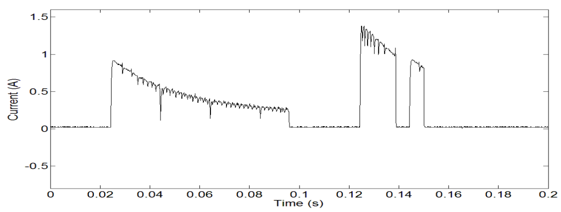


Fig. 10. Current consumption of Futaba S3004 moving 20 degrees.

reaching its set-point. The back-current of the digital servo is interesting as it is energy that is actually returned to the batteries. It would be possible to harvest this energy and use it again, although the amount of energy returned is quite small. Figure 12 shows the amount of energy returned when turning the HS-5645MG servo through different angles; these values are reduced by about a third for the HS-5245MG.

Figure 13 shows the overall energy consumption of each servo. Of the servos tested, the HS-55 (analog), HS-5065MG and Futaba S3153 consume the least amount of energy per degree turn. The low torque they offer may not be suitable in all situations but they worked remarkably well with our nodes during the experiments. The figure also shows that the current consumption given in the data sheets can be misleading in

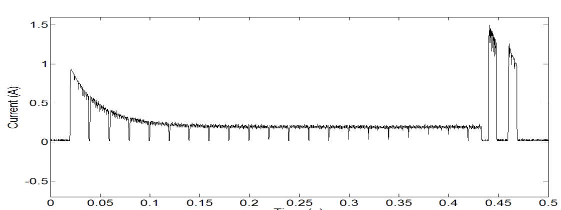


Fig. 11. Current consumption of the Futaba S3004 moving 120 degrees.

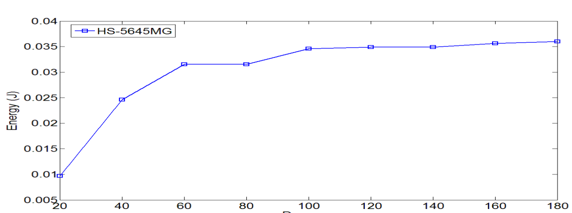


Fig. 12. Returned energy for a digital servo over different degree turns.

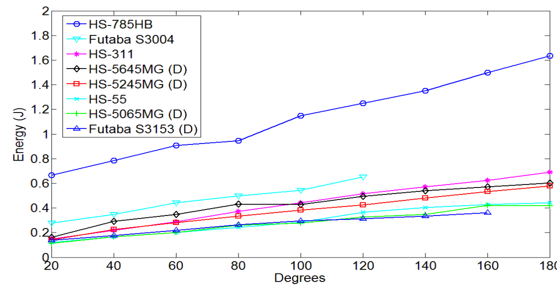


Fig. 13. Overall energy consumption of three different servos.

terms of the actual energy consumed (e.g. the HS-5645MG compared with the HS-785HB). When budget planning for WMSN energy, therefore, it is imperative to consider the specific requirements (panning angles, speed, and frequency) and to rely on energy measurements of the servos to verify their utility for target applications.

As all servos consume less energy once they reach steady state the slope of the curve should reduce somewhat. This effect is more pronounced for higher speed servos (both analog and digital) but less so, if at all, for the slower analog servos (HS-785HB and Futaba S3004) due to the high pulsing current around the set-point. Although an analog servo may be specified as having a lower power consumption on average, due to these larger pulses around the set-point they can, in fact, consume more energy than a digital servo of similar specification. This can be seen with the HS-5645MG and the Futaba S3004 where the former consumes significantly less energy even though they operate at approximately the same angular velocity. A cautionary point should be made with regard to the use of a cog-mechanism - such as the one supplied with the HS-785HB. To move this servo 180 degrees using the cog-mechanism takes a great deal longer compared with the other servos. Although this allows for finer-grained movements the reduction in angular velocity increases the energy consumption significantly in this case.

To illustrate the energy consumption of the servos relative to our overall system, we carried out a simple calculation for the energy usage of each component over a period of 15 minutes. The PIR sensor is always on, as this is the cheapest and primary source of detection. The audio sensor is on for 10 seconds every 2 minutes, while the camera sensor is on for 10 seconds every 3 minutes. The DSP is on whenever the audio or camera is on. The mote radio uses a duty cycle of 7%. The servo turns 90 degrees on average when activated, which is every second time the camera is on. Figure 14 shows the overall results. Although the servo consumes an appreciable amount of energy i.e. 0.35J per 90 degree panning[7], it is still much lower than the DSP energy consumption when duty cycled in this manner. This result implies that the selective use of servos to improve the quality of images in WMSNs is indeed a feasible and beneficial option.

[7] As is the case for the HS-5245MG for example.

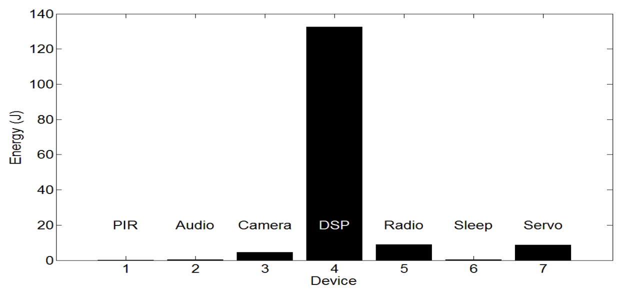


Fig. 14. Comparison of servo energy consumption with other system components when duty cycling considered.

V. Conclusion and Future Work

We have presented an analysis of the benefits of using a servo-mechanism to offer extra degrees of freedom in a Wireless Multi-media Sensor Network. We showed that although the servos can use a significant amount of energy they are still feasible if controlled in an intelligent manner. We looked at a number of different servo types and discussed about the possible ways of incorporating these into an hierarchical structure.

We also briefly described our new tightly integrated wireless multi-media node design along with a conceptual framework which views each node as consisting of an internal hierarchy of tiers. We are currently considering the question of the optimal way to use the multi-modal information available within this framework to maximise the information for a specific cost given lifetime, energy and user policy constraints.

In terms of servo choice, our results suggest that digital servos offer a good solution in terms of speed and energy; although they are somewhat more expensive than their analog counterparts. Another possible solution is to build a custom made servo tailored specifically for the application at hand. The open servo project is a nice example of how to do this [19].

Study of problems with mechanical wear remains an open issue for future work. However, the number of rotations for a relatively cheap servo-motor is on the order of 300,000 [16] - more than enough for the applications we are considering.

As a final point: it will be necessary to have some sort of determination as to when the servo gets overloaded once at its set-point. Even a slight loading of the servo can draw more current than might be accounted for in an energy budget. The more the servo is moved away from its set-point the more current it will draw - in some cases this can be more than 500mA average current (1A peak). Ideally the servo should be switched off once this point is reached. Some analog servos automatically switch off once the control signal is removed however the digital servos we tested remain on once power is applied even without a control signal. Assuming no load, the current draw in this case is simply the idle-current which can still be quite costly as shown in Table I. Once a load of any sort is applied, the cost increases significantly. It will therefore be necessary to have some sort of *guard-band* in the WMSN energy budget to account for overloading current.

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