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Studying the Feasibility of Energy Harvesting in a Mobile Sensor Network

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ABSTRACT

We study the feasibility of extending the lifetime of a wireless sensor network by exploiting mobility. In our system, a small percentage of network nodes are autonomously mobile, allowing them to move in search of energy, recharge, and deliver energy to immobile, energy-depleted nodes. We term this approach energy harvesting. We characterize the problem of uneven energy consumption, suggest energy harvesting as a possible solution, and provide a simple analytical framework to evaluate energy consumption and our scheme. Data from initial feasibility experiments using energy harvesting show promising results.

1. INTRODUCTION AND BACKGROUND

Wireless sensor networks [1] are an exciting new area of research. They belong to the class of ad-hoc networks, where the individual nodes have limited sensing, computation, communication and energy. The (envisaged) large scale of such networks prohibits human intervention for network maintenance. One of the very scarce resources for these types of networks is energy. These networks are expected to have a long lifetime (weeks to years) without human intervention for energy replenishment (recharging or changing the batteries). Human intervention is undesirable since large number of nodes imply high operational cost.

Current approaches to energy management mainly focus on low power architecture and low power network design at different communication layers. These include (Figure 1):

- Low power hardware architectures
- Low power software techniques
- Limiting transmission range and power control at physical layer to bound device consumption [2].
- Low power MAC mainly by increasing MAC layer sleep time of the nodes [3].
- Dynamic configuration of nodes with extra deployment of them in any geographic region for sleep cycles in higher time granularity [4].
- Geographic and power aware routing to bound network traffic [5].
- Data Aggregation to increase the good put of the network and to suppress unnecessarily data traffic [6, 7].

In parallel, there has also been active research in environmental power scavenging techniques [8]. There is also some work on energy replenishment in a sensor network using robots [9]. In this project a robot is used to recharge the sensor nodes connected to plants. The robot is also used to water the plants. In terms of harvesting energy from the environment, the current mature technology is based on solar cells. While solar cells are attractive outdoors, they have poor indoor performance especially with fluorescent lights sources. They also suffer from a large dynamic range outdoors. There is a difference of up to three orders of magnitude between the available solar power in cloudy, shadowy and sunny environments. Other potential energy sources are vibration, fuel cells, thermal diffusion and acoustic noise. These new technologies are not mature, which precludes their use in the near future. Solar cells remain the current main source of ambient environmental energy.

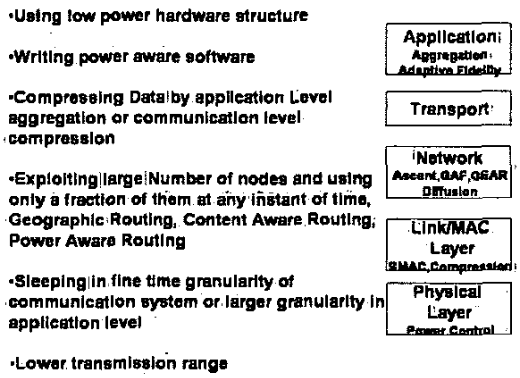

Figure 1: Low power network design techniques

2. THE ENERGY HUNTING MECHANISM

Consider a geographically distributed sensor network composed of many individual nodes. We assume that some of the nodes are capable of recharging themselves using energy available in the environment using solar panels. We call these nodes *energy producers*. The rest of the nodes only consume energy in computation and communication. We call them *energy consumers*. There are two key problems to be addressed. Energy producers need to work with a non-uniform geographic energy distribution, i.e., the available energy pattern in the network environment may be completely different from the energy consumption pattern and it may lead to energy starvation in some portion of the network. This may ulti-

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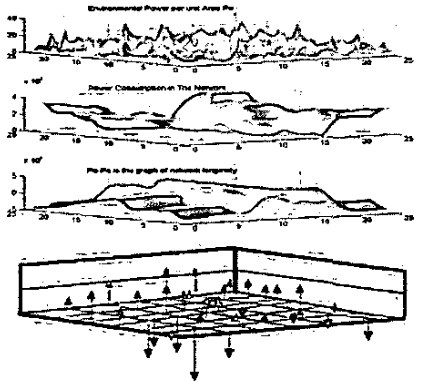


Figure 2: The top figure is available environmental power, the next figure is power consumption. The difference of the two is an important factor in longevity of the network. The last figure shows discrete samples of power distribution across the network nodes.

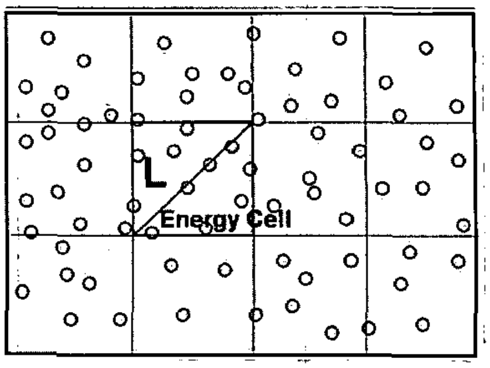


Figure 3: Energy Cell defines the territory of each robot and its zone of service. The area spanned by the network is divided into Energy Cells. The number of robots per cell depends on the number of static client nodes, the rate of their energy consumption and available environmental energy

mately result in a fragmented network and uneven sensor coverage because some set of nodes has been completely energy depleted. The second problem is for the energy producers to deliver the energy they have gathered to the consumer nodes.

We propose a method to exploit robotic mobility by having energy producers be mobile robots. These nodes try to keep themselves recharged by moving to locations with abundant energy supply. Once charged, they migrate to the service areas in the network for delivering energy to the (static) consumer nodes that have requested energy. In essence, mobile energy producers act as *energy-equalizers* in the network by carrying energy 'payloads' from areas where environmental ambient energy is plentiful to areas where it is either unavailable or being used faster than it can be harvested. Although in this paper we explore energy harvesting via mobile nodes, related problems use mobile nodes for other purposes, such as to maintain network connectivity [10] or to improve localization [11, 12]. It is interesting to note that the mobile nodes can also serve other purposes such as maintaining network connectivity.)

3. ANALYTICAL DISCUSSION

3.1 Self Contained Network

We consider the sensor network to be a closed energy system consisting of producers and consumers. Each node is capable of producing energy with rate $P_p(i,t)$ and consumes energy with rate $P_c(i,t)$. The network longevity depends on $P_p - P_c$ over the entire network (Figure 2). At any instant of time the amount of energy consumed at node i is:

$$E(i,t) = \int_{t_0}^{t} [P_p(i,t) - P_c(i,t)]dt \tag{1}$$

The network energy is the summation of the individual node energies across the network:

$$E(t) = \int_{t_0}^{t} (\sum_i [P_p(i,t) - P_c(i,t)])dt \tag{2}$$

In fact, since consumption and production are discrete quantities across the nodes of the network. If we get energy samples across the network then we have the discrete energy distribution function (Figure 2). The summation of the discrete energy function across the network is the network energy. A node is self contained if:

$$E(i,t) > 0; \forall t > 0 \tag{3}$$

Since energy consumption and generation varies across the network, some nodes may be self contained while others may not. For example, a node sitting in shadow and actively sensing and communicating would have a large consumption and so probably would not be self contained, while a lightly used node in bright sunlight will have plentiful energy. The goal of our system is to detect these kinds of energy imbalances and even them out by moving nodes.Thus we can define the network to be self-contained if:

$$E(t) > 0; \forall t > 0 \tag{4}$$

Note that it is a necessary but not sufficient condition for a static network to be self contained mainly because the formula does not consider energy distribution variation. If we assume that energy overhead of the energy-equalizing algorithm is zero, then there exists an algorithm such that by implementing that algorithm there would be no energy failure of any element of a self-contained network.

In practice the overhead of such an energy-equalizing algorithm may not be be negligible,specifically in our case, in which we exploit motion. Then a network is a self-contained network if:

$$E(t) - E_{overhead} > 0; \forall t > 0 \tag{5}$$

where, $E_{overhead}$ is the overhead of the energy harvesting algorithm. Notice that $E_{overhead}$, is not a fixed value and to a great extent, depends on the variance of the environmental energy availability , spacial distribution of the network and number of static nodes.

3.2 Energy Cells

Let the maximum amount of energy that any mobile node can store be E_{max}, the amount of energy it consumes to move (per unit distance) be E_{mov}, the maximum amount of energy any static node can store (and thus require a mobile node to transport) be $E_{payload}$. The longest profitable distance a mobile robot can move is:

$$\frac{(E_{max} - E_{payload})}{(2 \times E_{mov})} \tag{6}$$

We divide the network into service zones of linear size L (we use square service zones of diagonal L). Each such zone is called the *Energy Cell Area* (ECA) and it shows the zone of service or the territory of a mobile node (Figure 3). This defines a minimum bound on the number of serving robots needed in the network:

$$\text{Number of Serving Robots} \geq \frac{A}{ECA} \tag{7}$$

3.3 The Effect of Energy Availability and Network Consumption

Energy cells determine a theoretical minimum bound on the number of robots but the actual number of needed service robots may be larger depending on the network consumption and the available environmental energy. If we assume the density of static nodes is Δ and the network coverage area is A, also assume that average node's power consumption is P_c and average power availability for production is P_p then the minimum number of service robots is:

$$\text{Number of Serving Robots} \geq (\frac{A}{ECA}) \times (\frac{P_c}{P_p}) \times (ECA \times \Delta) \tag{8}$$

In this formula the parameter $\frac{A}{ECA}$ is the number of Energy Cells, the $ECA \times \Delta$ stands for expected number of static nodes per Energy Cell and $\frac{P_c}{P_p}$ is the rate of power consumption (discharging) compared to the rate of power production (charging) in cells. The value of P_c is the average value of consumption of the nodes and the value of P_p is the average power production (i.e. average power per unit area multiplied by the solar panel area). Note that the efficiency of the solar charging system may also be accounted for in the calculation. Also notice that increasing the number of robots can compensate for the effect of low available energy density across the cells, although, this may not make sense beyond a certain limit. Finally, the effect of large variance of available energy distribution can be compensated by increasing the energy capacity (battery size) of each robot. This will increase its energy searching territory.

4. EXPERIMENTAL TESTBED

Creating a meaningful experiment needs large number of static nodes and mobile nodes. We have created a smaller version of such a testbed for our experiments [13, 14]. The current testbed (Figure 4) has 15 static nodes and three mobile robots. The static nodes are Berkeley motes [15]. We use them as our network elements capable of sending and receiving packets. They also act as beacon elements replying to robot queries. These beacons are used by the robots to localize themselves.

The robots used in our experiments are Robomotes [16] that we have designed previously. They are able to send queries to the network and get replies from the beacons to localize themselves. The algorithm for localization is simple. Each robot localizes itself to the centroid of all static nodes from which it receives beacons [17]. This localization scheme, with all beacons calibrated in range, gives an accuracy of approximately 0.3 grid spaces and variance of 0.15 grid spaces. The grid spaces are 2 feet apart.

Transmission ranges of all the beacons are calibrated to be one-grid cell with an auto calibration routine we developed. This currently provides us a three-hop network. Both robots and static nodes can send information packets destined to a specific destination node in the network. We currently use flooding as our routing mechanism.

Each robot constantly sends a query to the network to find out if any static node needs service (i.e. energy replenishment). The static node(s) that needs the service replies back with its location and the amount of time it can survive without assistance. The robots then select the node with most urgent service and navigate across the testbed toward the service location.

The robots have wheel odometers, which produces 10 pulses per inch. They also have a compass with resolution of better than 5°. The combination of RF localization service, wheel odometer and compass enables s reasonable navigation across the testbed. A camera suspended above the testbed is used for ground truth[18].

The robots can be charged via a wall adapter or an optical docking station. The charging time with wall adapter is 3 hours and with the optical docking station it takes about 6 hours. The robots also can go to deep sleep for minimum power consumption.

5. EXPERIMENTS

To begin to understand the viability of energy harvesting we performed a series of experiments using our testbed. These tests are:

- quantifying the network power consumption
- quantifying robot parameters (energy consumption, production and capacity)
- characterize the running overhead of the robots

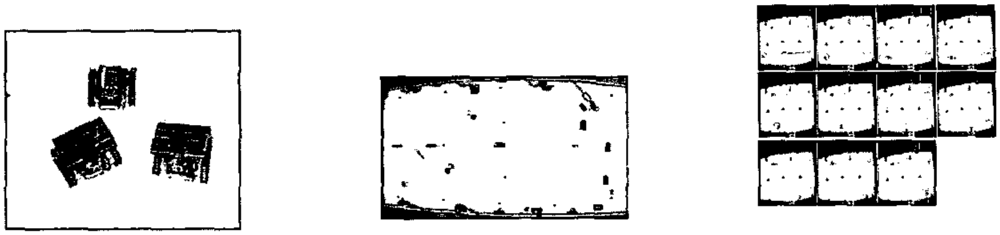
We also calculated the necessary number of robots for running on our testbed.

5.1 Maximum Network Consumption: Simple Ping

The first experiment characterizes the lifetime and energy consumption of the network over different traffic patterns. The energy reservoir of the network is a known parameter, which is the battery capacity of individual nodes multiplied by number of nodes. Energy consumption of the network is the other important parameter for determination of the network lifetime. Energy consumption is dependent on network activity or network traffic.

We ran multiple ping experiments with different transmission rates each for 30 minutes and measured the actual number of packets passed through the network (Table 1). These measurements are obtained using snooper nodes across the network that listen constantly to the network traffic and dump data on a central debugging PC machine. Table 1 shows that the amount of information which can pass through the network, is maximized at certain point. This maximum capacity point is also the maximum energy consuming point for the network. We call it Peak Consumption Point. Note that in reality the actual power consumption may be more than the peak energy point if the amount of information sourced in the network is more than the network capacity, which waste the energy resources without any improvement in traffic. Clearly this is not a good design point.

At the Peak Consumption Point the network passes 16700 packets per 30 minutes or 9.3 packets per second. Since there are only



(a) robots with solar cells

(b) testbed from localization web-cam

(c) Navigation of the robot across testbed from point (3,1) to point (3,7)

Figure 4: Robots, testbed and navigation of robots across the testbed.

15 nodes in the network this works out to 0.62 packets per second per node. Nodes in the network are either transmitting or receiving (or idle) with almost the same amount of energy consumption in receiving and idle state. The packet transmit time is approximately 25 ms, the energy that the node consumes in transmission is 60mW, in reception 36mW and in sleep it is only 240 μW. This suggests that the maximum node consumption is obtained by multiplying the transmit power by the maximum percentage of transmit time to which we add the reception or idle power consumption for the rest of the time. Using numbers from our testbed:

Transmit time = 25ms × 0.62 = 0.015 sec = 1.5%
Max Node consumption=60 mW×1.5% + 36mW×98.5%=36.4 mW

This shows that with the current MAC and routing protocol the consumption of the multi-hop network is mostly dominated by idle power, which is basically reception power (since the radio listens in idle mode). This power consumption may increase if we have better routing protocol or a MAC protocol with RTS/CTS, enabling higher amount of traffic that network can carry. Finally it also shows that by being able to change some percentage of idle time from receiving to sleeping we may gain a lot of power saving.

Using current values for static node battery capacity in our testbed (550mWh) allow us to compute network lifetime:

550mWh / 36.4mW = 15.1 hour

5.2 Robot Energy States and Robot Territory

Mobile nodes in our system have different energy states (Table 2). The main states are transmitting, receiving, moving and charging. Charging state gives a variable rate, depending on the available environmental energy. The charging value in Table 2 is the typical value for our optical docking station.

Based on our previous discussion for the robot territory and the fact that the robot's moving power consumption (per unit distance) is 0.210 J/inch, the robot battery capacity is 1100mW and each static node has capacity of 550mWh, we compute the diagonal of ECA:

$$\frac{(E_{max}-E_{payload})}{(2\times E_{mov})} = \frac{(1100mW-550mWh)}{2\times 0.21_{inch/joule}} = 110foot$$

This clearly shows that a robot may cover a large, building-sized territory. Although this appears to be a promising result, we note that the rate of charging of the robot is very close to the rate of discharging the nodes. This requires a large number of serving robots. In this example we have:

Number of Serving Robot $\geq (\frac{A}{ECA}) \times (\frac{P_c}{P_p}) \times (ECA \times \Delta)$

Since in our case ECA is the whole network ($A_N = ECA$), we obtain the following numbers for our testbed.

Number of Serving Robots $\geq (36.4/120) \times 15 = 4.55$

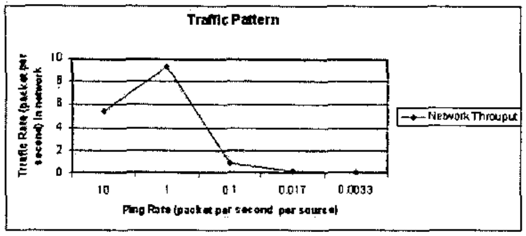
This result shows the importance of the consumption pattern. Note that this number of serving robots is necessary for worst traffic condition and guaranteeing the network longevity. In practice the number of serving robots may reduce depending on expected reliability.

5.3 Overhead of the Algorithm

The previous two experiments give an estimate of the robots territory and the actual number of needed robots for maintenance of the network longevity. However, we have not yet considered the overhead of running the algorithm. There are two type of overhead associated with our algorithm. The first one is the communication overhead on the network for energy queries and the replies. The second one is the movement overhead (due to paths taken by the robot which are longer than optimal).

We ran a series of experiments to estimate the overhead associated with the suboptimal paths the robot takes. We programmed the robot to go from different initial points to destination points and logged the path they actually navigated. Figure 4(c) shows one example of such navigation. In this figure it is clear that the robot starts from location 3,1 to reach location 3,7. The actual path taken is shown in the figure. The average path has 30% overhead (sampled on 100 paths) compared to the straight-line path. If we neglect communication overhead, and also neglect the overhead of sink to source movement due to our small testbed size, and only consider the movement overhead this corrects the requirement for the maximum number of robots to be:

Number of Serving Robot $\geq 4.55 \times 1.3 = 5.9$



Ping Rare	Number of packets received in 30 minutes
10 Packets/Sec	9723 Packets
1 Packet/Sec	16700 Packets
1 Packet/10 Sec	1504 Packets
1 Packet/60 Sec	303 Packets
1 Packet/300 Sec	65 Packets

Table 1: The table shows the rate of packets transmitted from the ping source and the throughput of the network in 30 minute experiment time. The graph shows the calculated per node throughput traffic vs. the source ping rate.

6. FUTURE WORK

Current work is a preliminary analysis of the applicability of such type of systems. Clearly, we see that the results are promising. We leave a more comprehensive study with probabilistic approaches for later study. We also develop the actual energy equalization algorithm to run on such a network.

Current testbed has apparently a limited scope of operation. There are several limiting factors in the current system such as:

- Low Number of robots
- Low Number of static nodes
- Limited geographic scope

While this is true, on the other hand our current testbed provides a very reliable and controlled test environment for preliminary algorithmic experiments. While we are doing more experiments with our current system but also we are developing a more reliable testbed. Our newer testbed will target in the long run:

- 50 Active robots
- More than 50 static nodes
- Multiple optical docking station
- Building size network distribution
- More efficient routing
- Nodes sleep in idle time

State	Energy
Move (2"/Sec)	-420mW
Transmit	-60mW
Receive	-36mW
Sleep	-240μW
Charge	120 mW

Table 2: Measured energy consumption or production of the robot in different states.

The new robots will have enhanced features such very lower power consumption in movement state, higher speed,excellent odometer feedback system for reduced movement overhead and very precise object avoidance system for in building navigation. We target larger geographic scopes and lower number of robots to static nodes ratio in future.

7. CONCLUSION

In this paper we introduced a new paradigm of energy management and equalization using mobility. This approach can increase the network longevity.If the net consumption rate is lower than the possible harvesting rate,enough mobile nodes can provide a self-sustaining system. We defined the robots territory and the number of active serving robots needed in those territory areas.

We also described the development of a testbed for finding the practical balances for such high longevity network. We found that in our network of 15 static nodes with maximum possible traffic we need about 6 robots to guarantee network longevity. This is a about 0.40% number of robots to number of static nodes ratio for guaranteeing network lifetime. In practice the actual number of robots can be less based on the degree of expected network availability.

The results clearly demonstrate the applicability of our approach to energy maintenance.We showed that an unmodified network would partition in less than a day can be made sustainable with the addition of 40% mobile nodes. This result demonstrates that the addition of a few, relatively inexpensive robots (less than twice the cost of static nodes) can make sensor nets self-sustaining.

8. ACKNOWLEDGMENTS

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9. REFERENCES

[1] Deborah Estrin, "Embedded Everywhere", *National Academy of Engineering,2001.*

[2] R. Ramanathan and R. Hain, "Topology Control of Multi-hop Radio Networks using Transmit Power Adjustment", *Proc. IEEE Infocom Tel Aviv, Israel,Mar 2000*

[3] Wei Ye, John Heidemann and Deborah Estrin, "An Energy-Efficient MAC Protocol for Wireless Sensor Networks", *In Proceedings of the 21st International Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM 2002), New York, NY, USA, June, 2002*

[4] Alberto Cerpa and Deborah Estrin, "ASCENT: Adaptive Self-Configuring Sensor Networks Topologies", *In Proceedings of the Twenty First International Annual Joint Conference of the IEEE Computer and Communications Societies, NewYork, NY, USA, June,23-27,2002.*

[5] Yan Yu, Ramesh Govindan and Deborah Estrin, "Geographical and Energy Aware Routing: A Recursive Data' Dissemination Protocol for Wireless Sensor Networks", *UCLA Computer Science Department Technical Report UCLA/CSD-TR-01-0023, May,2001.*

[6] S. Madden, R. Szewczyk, M. Franklin and D. Culler, "Supporting Aggregate Queries over Ad-hoc Wireless Sensor Network" *Workshop on Mobile Computing and Systems Applications, 2002*

[7] Chalermek Intanagonwiwat, Ramesh Govindan and Deborah Estrin, "Directed Diffusion: A Scalable and Robust Communication Paradigm for Sensor Networks", *In Proceedings of the Sixth Annual International Conference on Mobile Computing and Networks (MobiCOM 2000), August 2000, Boston,*

[8] Jan M. Rabaey,M. Josie Ammer, Julio L. da Silva Jr., Danny Patel, and Shad Roundy, "PicoRadio Supports Ad Hoc Ultra Low-Power Wireless Networking", *IEEE Computer, vol.33, (no.7), IEEE Comput. Soc, July 2000. p.42-8.*

[9] A. LaMarca, D. Koizumi, M. Lease, S. Sigurdsson, G. Borriello, W. Brunette, K. Sikorski, D. Fox, "PlantCare: An Investigation in Practical Ubiquitous Systems", *Intel Research, IRS-TR-02-007, Jul. 23, 2002*

[10] Maxim A. Batalin,Gaurav S. Sukhatme, "Efficient Exploration without Localization", *To appear in International Conference on Robotics and Automation, ICRA2003*

[11] Nirupama Bulusu and John Heidemann and Deborah Estrin and Tommy Tran, "Self-Configuring Localization Systems: Design and Experimental Evaluation", *To appear On ACM Transactions on Computer Systems,September 2002*

[12] Nirupama Bulusu and Deborah Estrin and Lewis Girod and John Heidemann, "Scalable Coordination for Wireless Sensor Networks: Self-Configuring Localization", *In Proceedings of the 6th IEEE International Symposium on Communication Theory and Application*

[13] Test bed webpage: *http://www-robotics.usc.edu/projects/robomote/testbed/*

[14] Mohammed Rahimi,Rohit Mediratta, Karthik Dantu, and Gaurav S. Sukhatme, "A test bed for experiments with Sensor Actuator networks", *http://robotics.usc.edu/ robomote/testbed/techreport.pdf*

[15] David Culler, "A Network-Centric Approach to Embedded Software for Tiny Devices", *DARPA workshop on Embedded Software.*

[16] Gabriel T. Sibley, Mohammad H. Rahimi and Gaurav S. Sukhatme, "Robomote: A Tiny Mobile Robot Platform for Large-Scale Sensor Networks", *Proceedings of the IEEE International Conference on Robotics and Automation (ICRA2002), 2002*

[17] N. Bulusu, J. Heidemann and D. Estrin, "GPS-less Low-Cost Outdoor Localization for Very Small Devices", *IEEE Personal Communications Magazine, Special Issue on Smart Spaces and Environments, October 2000.*

[18] Mezzanine,An Overhead Visual Object Tracker *http://playerstage.sourceforge.net/mezzanine/mezzanine.html*