Ballistic Deployment of WSN Nodes using Model Rockets

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ABSTRACT

Wireless sensor networks consisting of a large number of relatively inexpensive nodes are used in a variety of tasks. When being used in difficult to access terrain, or dangerous surroundings, such as often encountered in disaster scenarios, the deployment of a WSN becomes a challenge. In this paper we introduce a novel approach for deploying a WSN: We propose using small-scale model rockets as a cheap, reliable and time-efficient way to deploy a WSN. We discuss advantages and disadvantages over other approaches and provide experimental results to give an idea about realistic deployment costs, expected distribution of nodes and feasible launch vehicle configurations.

1. INTRODUCTION

There are many applications where a wireless sensor network needs to be deployed. For some applications such as smart cities or agricultural WSNs the networks needs to be be structured: Deployment is planned, and nodes are placed at predetermined positions. In other scenarios, such as disasters or large scale environmental monitoring, a random, unstructured deployments are sufficient. When manual deployment by humans is not desirable (e.g. due to costs or speed) or not feasible (e.g. due to inaccessible terrain), automated deployment methods need to be considered. We argue that a so-far not researched method can offer benefits for many applications: Deployment using small-scale rockets. We will show that this approach is cheap, scalable, easy-to-use and enables much faster deployments than other methods.

In Section 2 we will present existing WSN deployment methods, and show how rocket-based deployments differs from them. Scenarios for rocket-based deployments are introduced in Section 3 and the used rockets and sensor payloads are described in Sections 4 and 5. Results of test launches are given in Section 6. We are discussing further aspects regarding the applicability of the presented approach in Section 7 and finish by summarizing and lining out future work in Section 8.

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2. DEPLOYMENT METHODS

There are several ways to deploy a WSN depending on the environment, the size of the desired deployment and the needed equipment. Table 1 gives an overview.

2.1 Manual Deployment

This is the baseline approach. Nodes are placed by humans. This gives the highest degree of control and intelligence during the deployment process. It is however not suitable for dangerous or hazardous environments. This method is basically very cheap for small deployments. No additional equipment is needed. Mobile applications [1, 8] helping with deployment and documentation exist. When scaling up and needing to employ large amount of people, costs will rise. Therefore, there are several alternatives with the help of technology.

2.2 Ground Robots

WSN nodes can be deployed by ground robots. Suitable robots are already established and commercial systems exist for reconnaissance operations[1]. Ground robots allow positioning nodes intelligently. They can either be autonomously or remotely operated. The challenges are that suitable vehicles are relatively expensive and need a specially trained operator. They have limited storage capacity and need additional mechanics for the dropping functionality. A system for deploying a WSN from ground robots has been presented in [9]. This deployment method can access regions, a human can not (conversely it may also fail to access regions a human could). Ground robots systems can be operated indoors and outdoors and can be used in scenarios too dangerous to send humans.

2.3 Airplanes

A seemingly well-known method that has been mentioned since the beginnings of WSN research are large scale deployments by airplane. WSN nodes are dropped while flying over the target area. The main disadvantage is the high cost for operating an airplane. This method will only be effective for really large deployments. This may also be the reason why, despite being mentioned for years, we do not know of any

[1] `http://www.taurob.com/`

	Manual	Ground Robots	Airplanes	Multicopters	Rockets
Network Structure	Structured	Structured	Random	Structured	Random
Fixed Costs	Low	High	Very High	High	Low
Scalability	○	⊖	⊕	⊖	⊕
Hazardous Environment	⊖⊖	○	⊖	○	⊕
Usability	⊕	⊖	⊖⊖	⊖	⊕⊕
Deployment Speed	○	⊖	○	⊖	⊕⊕

Table 1: Deployment options for WSN networks

research project that has actually deployed a WSN in such a way. Obviously, this method can only be used outdoors.

2.4 Multicopters

WSNs could be deployed by UAVs. Structured deployment is possible. The drones can either be autonomously or remotely operated. The problem of limited storage capacity is even more pressing than in the case of ground robots. The weight and size of dropping mechanisms further reduce a drone's payload. Systems using a model helicopter have been presented in [3, 6]. Scaling through using multiple drones becomes expensive fast. A related approach are model airplanes. They would provide longer operating times, but the trade-off is an unstructured, less precise deployment as an airplane can not hover, and is hard to fly near ground level. A flying drone can access regions unreachable for vehicles or humans. Such a system is well suited for outdoor operation. Indoor operation is possible but limited. Flying drones can be used in scenarios too dangerous to send humans.

2.5 Rockets

As we will show in the remainder of this paper, deploying WSN nodes by model rockets is cheap and very scalable. Rockets can reach areas inaccessible to humans or ground vehicles. Low cost of individual rockets is a significant advantage. They are expendable and can be used in weather or environmental conditions where you would not dare to risk a drone or robot. A rocket-based deployment system does not need a specialist to operate. Everyone who has ever launched a fireworks rocket, can use the system. As with the other unmanned approaches, rockets can be used in scenarios too dangerous to send humans. Obviously, this approach is only suitable for outdoor deployments.

3. SCENARIOS

We will discuss three scenarios that can profit from rocket-based deployment. What all the presented scenarios have in common is the requirement to cover a large area. Using rockets, an initial deployment can be fast and cheap regardless of the situation on ground. For the cost of one flying drone you can launch a large number of rockets. Furthermore, launching rockets does not require specially trained operators.

3.1 Environmental Monitoring of Inaccessible Regions

One of the earliest applications proposed for WSNs is the large scale monitoring of environmental conditions. Considering rain forest or mountain areas, it is easy to see, that sometimes the hardest part is accessing the region to deploy the actual nodes. Using rockets nodes can be deployed from the periphery. In these scenarios multicopters would also be possible, but rockets have the potential to be cheaper and much faster.

3.2 (Natural) Disasters

A common scenario for node deployment are natural disasters. In such a case with destroyed infrastructure you might want to deploy a WSN for monitoring or communication purposes. After a large and unexpected earthquake having a large number of nodes measuring seismic activity might be desired. After a volcanic eruption such as the Eyjafjallajökull eruption in 2010 it might be desirable to have a sensor network measuring carbon monoxide or sulfur levels. In disasters where humans are affected it is possible to distribute panic button devices to potential survivors. These nodes might just send an emergency beacon or even allow two-way communication with rescue crews.

Sensor nodes can be cheap, and large-scale WSNs are designed in such a way that losses can be tolerated from the economic and technical perspective. Not so for drones or autonomous ground vehicles: They are expensive and usually not considered expendable. For many disaster scenarios rockets are therefore the better option. Consider volcanic eruptions with lots of ash still in the air or a radioactive fallout with localized spots of high radiation disabling electronic circuits. In these cases flying conditions are not suitable for drones. A large-scale rocket deployment is feasible, even when loosing a fraction of the payload.

3.3 Extraterrestrial WSNs

Today, single robotic probes are sent to extraterrestrial bodies such as Mars. Their speed is limited. For example the maximum speed of the mars rovers 'Opportunity' and 'Spirit' is around 5 cm per second, with an average speed of 1 cm/s [5]. There have been some long-term plans using autonomous robot swarms for exploration [4], however these are still largely future visions. On the other hand using small rockets to deploy small nodes is feasible today. A large area can quickly be covered: Due to lower gravity than on earth even less thrust is needed to deploy a node. A whole set of sensor node and attached rocket only weighs a couple of grams. A standard size Mars Rover could easily carry tens of such rocket-based sensor nodes, with the ability to communicate back to the rover after deployment. The tradeoff here is similar to the other scenarios: The rover itself is expensive, and complex. Bringing it to its destination is a costly adventure. Therefore, for the foreseeable future these devices will always use some super-careful ways of movement which is slow enough to give human operators one earth time to "react" despite long communication delays. A handful of rocket-powered nodes on the other hand are more expendable. Thus this concept is a very low-cost

(a) Starting

(b) Parachute

Figure 1: Launch Vehicle

Motor	Impulse	Avg. Thrust	Burn	Delay
C6-3	9.6 Ns	6 N	1.6 s	3 s
D9-5	19.5 Ns	9 N	2.1 s	5 s

Table 2: Used Rocket Motors

and feasible method to increase covered area and science output from extraterrestrial missions for probably less than 1 kg payload. For comparison, the Mars Exploration Rovers Spirit and Opportunity weigh 184 kg, Curiosity is a 900 kg vehicle.

4. ROCKETS

We used a classical model rocket for deploying the nodes. It consists of a cardboard tube and FDM-printed fins and tip (see Figure 1). Standard issue single-use rocket motors have been used. Motors differ in available thrust and ejection delay. After a motor burns out there is a delay before an ejection charge is fired, that will remove the tip and eject the parachute. Parachutes have been made from sheets of mylar (“space-blanket”). For single-use rockets the parachute might be omitted, if the rocket is light enough that there is no danger of harming a person. As the initial acceleration is high during the short burning phase, a rocket climbs most of its height during the delay phase. For the experiments we used two types of motors as shown in Table 2.

We tested two different rocket variants: The larger one was about 70 cm in length and used a tube with a diameter of 40 mm. Weight with parachute and motor was about 120 g. Depending on the sensor housings and ejection mechanisms up to 8 nodes can be carried by a single rocket. The smaller model was 35 cm in length with a 25 mm tube. Weight with parachute and motor was about 80 g. This rocket can carry 2 nodes. This is due to size and not weight constraints. The costs to build a single of these rockets including motor are approximately 10 to 15 EUR. For larger quantities prices would be significantly lower. While it seems more economic to use the larger rocket, the question is, whether the nodes will be distributed well enough. We look into this question in Section 6.

5. SENSOR PAYLOAD

The deployed nodes are size-optimized variants of the INGA WSN node [2]. They are built around an ATMega1284p processor with an IEEE 802.15.4 radio. A node is powered by a 3 V coin cell. The size of a node for the large rocket is 25x28 mm. The node used for the small rocket measures 38x18 mm. For both nodes the weight including battery is around 8 g.

For the 25 mm rocket a cylindrical capsule containing one node with battery has been constructed (see Figure 2a). Only the end caps of the cylinder have been printed using PLA, the main tube is made from paper in order to save weight and space. Due to the size constraints the battery needs to be put on top of the node in the enclosure, so a maximum of 2 node capsules can be loaded to the rocket. For the larger diameter rocket we created half-cylindrical enclosures, that allowed stacking pairs of enclosed nodes in the rocket tube (see Figure 2b). Thus 8 nodes can be fitted easily into the rocket. The node enclosures have either been equipped with a smaller version of the parachute or just a strip of mylar. While the nodes are light enough that they do not suffer any damage when being dropped without a parachute, we expected using a parachute would increase dispersal. We also assumed attaching a strip of mylar to the nodes without parachute would make recovering deployed nodes easier, as it is highly reflective.

However, during experiments, we found, that often nodes were not ejected, but stuck in the rocket tube due to friction. Different from Figure 1b, for later experiments we rewired the parachute, so the rocket would sail down upside down, giving the nodes a chance to slide out, if they are not ejected directly with the parachute. When this measure did not improve matters much, we got rid of the enclosures, just wrapping nodes in mylar, which leads to a less structured packaging within the tube. As the nodes are very light, they still get stuck easily. Finally we came up with a construction of two half-pipe “sleds” made from tin cans as can be seen in Figure 2c. The rocket parachute was wired in such a way, that it pulls out the sleds. Nodes are wrapped in mylar and put into the sleds. Two sleds face each other in the tube, thus there is only friction between the cans surface and the tube, but not between the tube and mylar from entangled nodes and parachutes. This proved to be a much more reliable way to eject nodes after the parachute is deployed.

6. EXPERIMENTAL RESULTS

To test the feasibility of the proposed rocket-based deployment method, we performed several test flights in a rural area in Northern Germany. The goal was to find a configuration that reliably ejects all nodes and get some idea about expected range and deployment area.

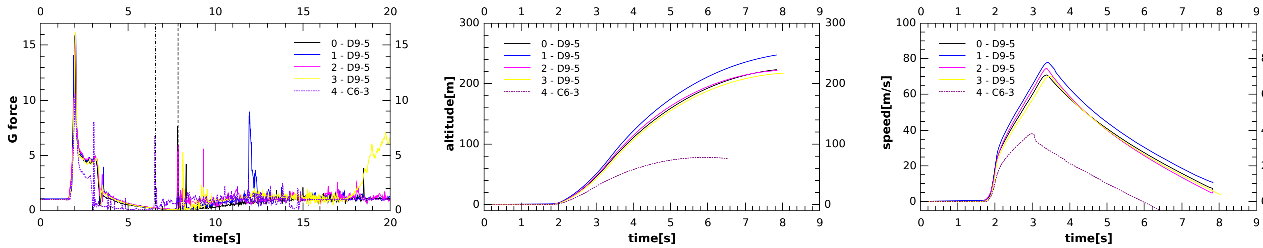
6.1 Flight Metrics

Since the used nodes are equipped with an acceleration sensor (Analog Devices ADXL345), we took some measurements during flight.

When constructing the payload it is important to know, that g-forces up to 15 g occur (Figure 3a) for short periods of time during launch. The measured accelerations are similar between different flights, which shows the stability of the rocket. Furthermore the measured acceleration curves match the thrust curve given in the motor's data sheet, which indicates that the measured values are reliable. While the experienced g-forces are not a problem for the electronics and MEMS sensors, it might be a mechanical problem when the payload is compressed during start. For example, this was one cause for not ejected nodes: Even when filling the tube only lightly, so that nodes easily fall out when turning the rocket 180°, the payload becomes much more compressed during flight, so when the parachute turns the

(a) Small rocket node and enclosure (b) Large rocket node and enclosure (c) Ejection sleds for large rocket

Figure 2: Rocket payloads



(a) G forces (b) Altitude (c) Speed

Figure 3: Flight Metrics

rocket after it is ejected, the nodes are stuck.

As the nodes did not have a pressure sensor or a gyroscope we can not measure altitude directly and neither is reliable data regarding the orientation of the rocket available. However, the altitude can be approximated using the accelerometer data assuming a perfectly vertical trajectory to the apogee. Thus we will slightly overestimate the altitude. After apogee and ejection of the nodes, they will tumble down and accelerometer data is not enough to determine altitude. Thus Figure 3b shows altitude over time until ejection. With the tested D9-5 motor the large rocket reaches heights of about 220 m while the C6-3 motor is only able to lift the rocket to about 70 m. Those values lie well within the range estimated in simulations using the OpenRocket[2] software. Maximum speeds reach almost 80 m/s for the D9-5 motor and 40 m/s for the C6-3 motor.

For the measurement flights, the larger rocket was fully loaded with 7 or 8 sensor nodes, the smaller one with 2. Considering that stronger motors and larger are commonly available for model rocket hobbyists, there is enough potential to increase the range or deploying heavier nodes (i.e. with larger batteries).

High altitude in the end means more covered area, as nodes, especially when using a parachute floating down, will distribute over a larger area (see Section 6.2). The final node placement is however highly dependent on the direction of the wind and hard to control. Therefore we also tested the maximum range of the rockets when doing a directed launch. Thus, the flight spans a large distance, while staying at a low altitude. The deployment could be more directed this way, as nodes would fall from a low altitude and thus their destination is less dependent on wind. The results for these tests can be seen in Table 3. While this mode of operation is often not allowed for model rockets, it would be possible to legalize it for certain applications and trained personnel. The trick is to make sure nodes are deployed while the rocket is still above ground (don't aim to shallow or use a motor with too large delay). Also, since nodes are ejected from a lower altitude, the spread between nodes from the same rocket will be lower. For a setup, where each rocket carries only one node, ejection may be omitted, and the rocket can double-act as a protective enclosure for the node.

Rocket	Engine	Angle	Range
large	C6-3	45°	171 m
large	D9-5	45°	370 m

Table 3: Maximum directed flying range

6.2 Deployment Characteristics

In this Section we will look at the pattern of nodes after deployment, and discuss some difficulties during experiments. Not all flights lead to a deployment. During first tests we found out, that while the rocket could easily lift any amount of nodes we could fit into the tube, too dense packaging and intermingling between the parachute and nodes can lead to a failure in deploying the parachute (see also Section 5). The ejection load was not strong enough to push out the parachute (and thus the nodes), leading to a rather condensed subterranean deployment of a WSN node stack (see Figure 5b).

While the chosen test area in rural Germany was generally large enough to accommodate the expected flying range of nodes and rockets, it is commonplace that fields are separated by small patches of trees. This is especially a problem for the rocket, which may glide a large distance with its parachute, and can easily get stuck in trees (see Figure 5a).

[2] http://openrocket.sourceforge.net

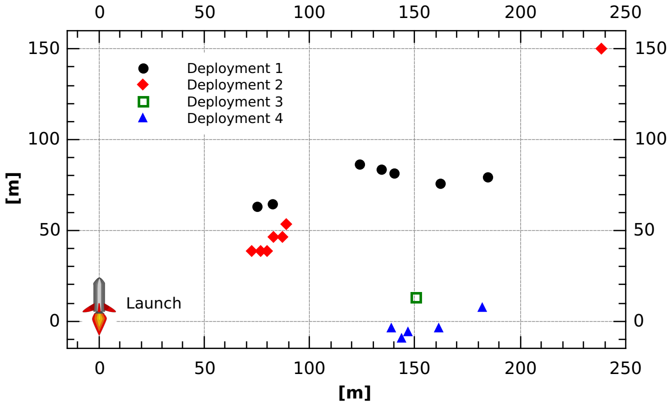


Figure 4: Deployed nodes' location

(a) Tree landing (b) Parachute ejection fail

Figure 5: Challenges during experimentation

This is not a problem for real deployments in inaccessible terrain where we suppose rockets to be single-use, however for the experiments presented here this caused some grief.

Lastly, even though all nodes had either a mylar parachute or a strip of mylar, due to their size it was often hard to find and retrieve all nodes after a launch, and some have gone missing. Some radio bearing techniques, or a more barren testing ground might help in the future. Locations of working deployments can be seen in Figure 4. Information about those deployments is summarized in Table 4.

Deployment 1 in Figure 4 used parachuted nodes in the large rocket with the sled construction (see Section 5). It can be seen that parachutes in the nodes lead to the largest spread compared to the other deployments. Especially for a single rocket loaded with many nodes this is most likely desired, as otherwise only large localized clusters get deployed.

#	Rocket	Engine	Node Enclosure	Parachute
1	large	D9-5	Mylar & Sleds	yes
2	large	D9-5	Plastic Enclosures	no
3	small	C6-3	Plastic Enclosures	no
4	large	D9-5	Plastic Enclosures	no

Table 4: Flights with deployment

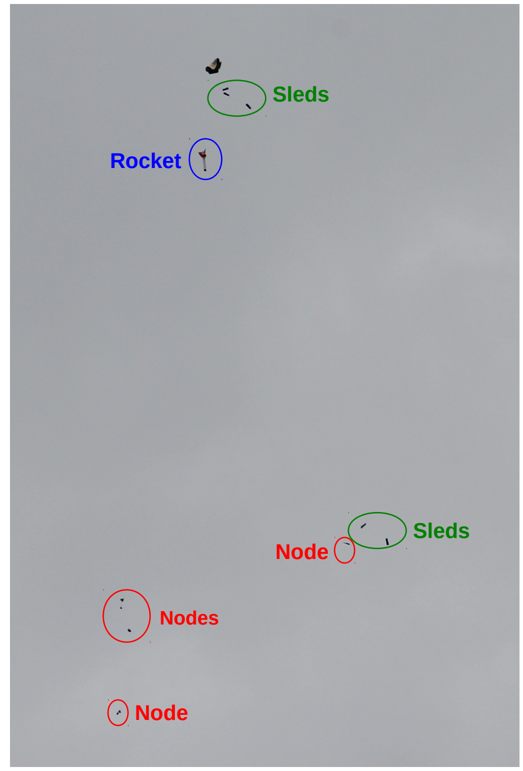


Figure 6: Nodes in flight after ejection using sleds

The difference in distance is due to the fact that the sleds are ejected one by one about a second after each other, and thus some nodes get ejected at a lower altitude. This can also be seen in Figure 6, which shows some nodes and sleds immediately after ejection.

In contrast, deployments 2 and 4 use the large rocket with nodes in plastic enclosures without a parachute (but with a strip of mylar). It can be seen that the deployments are much more localized. Some nodes have been lost in deployment 4. For deployment 2 one node was stuck in the rocket, and carried far away with it (see Figure 5a). In summary, without parachuted nodes, it probably does not make sense to use a rocket with many nodes, instead several smaller rockets with less nodes might be a better idea, as the final location between different launches differs, as can be seen by the different cluster positions between deployment 2 and 4. As emphasized by the position of the node remaining in the rocket in deployment 2, parachutes can be used to increase range significantly, however at the cost of precision.

Deployment 3 is from using the smaller rocket with a smaller motor and two sensor nodes. The second node and the rocket have been lost. Due to the smaller weight, the deployed node reached a distance compared to the other deployments.

For all experiments there was a slight wind from the "left" in Figure 4. Basically, while parachutes are important to reach spread and distance, they increase dependence on wind. The alternative are smaller rockets with less nodes, where the ejection delay and starting angle is tuned to eject nodes at a low altitude. What is desirable depends on the target scenario.

7. DISCUSSION

While we could show that deployments using rockets are not only feasible, but also cheap and scalable, there are additional aspects to consider when deciding whether rockets are the right deployment method for a given application.

7.1 Environmental Aspects

Is it desirable to launch loads of single-use rockets into an area? We would argue if you plan to randomly deploy WSN nodes in a region, the rockets are not a large problem. They are made largely from cardboard, and even the few plastic or metal components might be replaced with paper and propose less of an environmental problem than the nodes, and especially the batteries themselves. In this regard the rocket based approach is not worse than for example using an airplane. We would recommend neither for a nature conservation area. If the goal is to retrieve all nodes, structured approaches such as manually placing nodes are the only option.

7.2 Other Ballistic Approaches

Basically, a rocket is just a sophisticated way of "throwing" a WSN node. With this in mind, other approaches can be envisioned. Purely mechanical ones: The simplest idea is a loaded spring. As the energy that can be stored by a simple spring is not large only small distances could be covered. Probably slingshots or crossbow-like launching devices could improve that. The advantage of a rocket-based approach is still, that due to the chemical energy store, available thrust can be varied over a large range and the relation between weight/size and energy output is better compared to mechanical approaches. Regarding active systems, there are electromagnetic options such as a railgun (which uses induced magnetic fields) or a mass driver (basically a linear electric drive with an "open" end). Both options are researched by NASA for the applicability as large-scale launch device for spacecraft [10, 7]. However, these approaches are much more complex than a rocket and need lots of electrical energy. Thus, these options do not seem to offer a good compromise between performance, cost and complexity when fast ad-hoc WSN deployments are desired.

7.3 Connectivity

Due to the inherent indeterminism when doing a sequence of unguided rocket launches, the deployed network might not be fully connected. If the network is intended as a DTN, where data mules collect data, this is not a problem. Data mules might be people, multicopters or animals. If the intention was to deploy a fully connected network, the amount of nodes can be largely over-provisioned. However, a better approach would be to use rockets for the initial deployment, and then using one of the slower techniques such as multicopters to mend holes in the network [3].

8. CONCLUSIONS

We proposed deploying a WSN using model rockets. As we have argued, this method offers various advantages over common deployment methods, namely price, speed and scalability. Our experiments show that it is possible to deploy a WSN using rockets. Even the simple rockets used for our experiments are powerful enough to transport several nodes a sufficiently large distance. More powerful off-the-shelf rocket hardware is easily available. It turns out, that actually ejecting the nodes from the rocket is not trivial, especially if the nodes are very light. With heavier nodes using larger batteries this might be less of an issue, especially if the developed technique of having the recovery parachute turning the rocket upside down upon descend is used. For a large number of nodes, a friction-optimized sled construction can be used. As the proposed rockets are very light and unguided, it is hard to aim exactly. Thus, the presented approach is suitable for deployments where a large area needs to be covered. In the future we will do more large-scale experiments, where we will fire several similarly constructed and loaded rockets, to get some statistical data regarding distribution and gain more insight into the kind of network topologies that can expected from a rocket-based deployment and how precisely it can be controlled.

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