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Design considerations of UAV-aided automated meter reading

***Abstract**. This paper introduces a new approach of using mini/micro unmanned aerial vehicles (UAVs) for automatic meter reading (AMR) in rural areas where there are subscribers dispersed over a large area. Compared to other AMR systems, the use of UAVs brings many advantages including easy integration to existing AMR systems, flexibility, and low-cost and automatic operation. In this paper, design considerations and associated challenges of this approach are presented. In addition, simulation studies are given to prove the effectiveness of the proposed approach.*

***Streszczenie.** W artykule przedstawiono propozycję wykorzystania mini- i mikro- bezzałogowych statków powietrznych (ang. Unmanned Aerial Vehicles) w automatycznym odczycie liczników w obszarach wiejskich o niskim zaludnieniu. Omówiono zagadnienie projektowania systemu oraz problemów związanych z jego implementacją. (**Projektowanie systemu automatycznego odczytu liczników z wykorzystaniem bezzałogowych statków powietrznych**)*

Keywords: Automatic meter reading systems, unmanned aerial vehicles, navigation and localization system.
Słowa kluczowe: System automatycznego odczytu liczników, bezzałogowe statki powietrzne, system nawigacji

1. Introduction

Automatic meter reading (AMR), automatic collection of consumption, diagnostic and status data water meter or energy metering devices for billing, analyzing and troubleshooting, brings cost advantages to utility providers. AMR systems can also be used to turn services off or on at residences and identify problems remotely. In addition, they help utility providers better control their production and conduct system analysis. Also, by using AMR systems, utility providers help their subscribers control their consumption. Common forms of meter reading can be categorized into four types as in the following:

- **Fixed network-based meter reading:** A permanent network infrastructure is installed to collect meter readings [1]. Sometimes wired and wireless networks can be intermixed by design.
- **Walk-by meter reading:** Utility personnel carrying handheld computers with built-in receivers/transceivers gather the readings from metering devices.
- **Drive-by meter reading:** Utility personnel drive their vehicles and follow given trajectories. Meanwhile, the reading devices installed in the vehicles gather the readings automatically.
- **Touch-based meter reading:** Utility personnel carrying meter readers, handheld computers or data collection devices with a wand or probe, gather the readings from metering devices by touching or placing the read probes.

In spite of their several advantages, AMR systems entail substantial investments during implementation and maintenance phases [2]. Communication infrastructures are important parts of AMR systems. Therefore a large portion of total investment is spent on them and metering devices [2, 3]. Since AMR systems are generally long-term investments, utility providers may sometimes be reluctant to invest in these systems.

In this paper, design strategies of a novel automatic meter reading system for rural areas are given. Proposed system involves one or more unmanned aerial vehicles (UAVs) which follow their given trajectories using preloaded city maps to collect meter readings of subscribers over wireless links as shown in Fig. 1. After gathering the meter readings, the UAVs return and the collected data is fed into the AMR system. Finally, the data is statistically evaluated to provide information to the utility provider to improve its services. This system can be easily be integrated to improve the services of existing systems.

The proposed system eliminates the need for a fixed network infrastructure for collecting meter readings and sending data to a central database and is an alternative to walk-by and drive-by AMR systems. The proposed system requires metering devices with ZigBee wireless interfaces. Considering this significant investment, existing meters can be retrofitted with small battery-operated radio frequency (RF) modules for reading the metering data and sending this data over wireless communication channels. Overall, in this paper, UAV-aided AMR system is investigated.

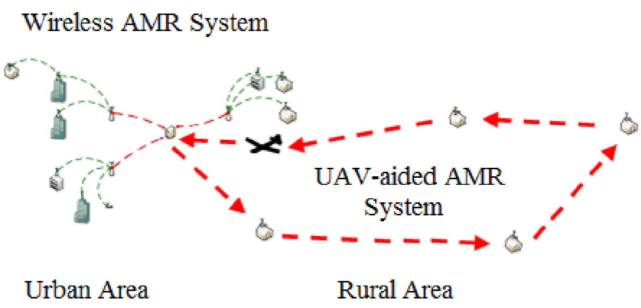

Fig. 1. UAV-aided AMR system

The paper is organized as follows. Related works are given in Section II. An automatic meter reading system using UAVs is explained in Section III. Simulation studies of the proposed navigation and localization system are also given in this section. Finally, the paper is concluded in Section IV.

2. Related work

Since AMR systems bring many advantages, AMR deployments are currently in progress in several countries including Australia, the United States of America, Canada, Germany and Italy. Due to this significant trend, several researches on this subject have been conducted in recent years. A short range wireless AMR system is proposed in [2]. In [3], a ZigBee based wireless AMR system is explained. In [4], the design of AMR data acquisition system is explained in addition to the details of the hardware of a wireless AMR module. In addition to this short range wireless systems, GSM and GPRS based systems have been proposed. In [5], a GSM based AMR system is proposed. In [6], a walk-by data collection system, based on prominent RF technology, using pocket PCs is proposed. Due to the startup and maintenance costs, most of the studies have been oriented to urban areas where there are a large number of subscribers.

Different from the AMR applications proposed for urban areas, the use of unmanned vehicles for AMR applications is proposed in [7]. The system proposed in [7] is specifically designed for rural areas where there are subscribers dispersed over a wide area. The main disadvantage of the system is the need for mechanisms to deal with dynamic real world conditions such as giving way to pedestrians, stopping at traffic lights and moving with other cars at the same time. Therefore the system proposed in this paper aims to overcome the drawbacks and limitations of the mentioned approaches and to solve the specific problems of the approach explained in [7].

3. The use of UAVs for automatic meter reading

The proposed system consists of many components including servers, databases, applications, wireless metering devices for subscribers, and micro/mini UAVs. In this section, UAV related design considerations and the lifetime expectations of wireless nodes are evaluated.

3.1. Communication

Communication infrastructures play key roles on the success of AMR systems and smart grid applications. Most AMR systems and smart grid applications involve both wired and wireless communication infrastructures. Generally, the investment cost of wired systems is more than wireless systems. As it is well-known, compared to wired AMR systems, deployment phase of wireless AMR systems is easier and takes less time besides being more flexible. Communication part of the proposed system includes battery-operated nodes and is based on ZigBee protocol.

The performance of the proposed system depends on several factors including data throughput, latency, jitter, packet loss, communication availability, range, and hardware reliability. In addition to the performance related factors, factors related to the effectiveness of a wireless network such as self-forming ability, node failure recovery, ease of deployment, ease of operation, and mobility need to be investigated. In this study, a simulation study is given to prove the effect of different parameters on battery-operated wireless interface lifetime, one of the main factors determining communication availability within a network.

3.1.1. Lifetime evaluations of battery-operated wireless interfaces

In order to evaluate the trade-off between the lifetimes of battery-operated wireless interfaces and the number of data transmissions, a simulation environment has been developed using MATSNL [8]. MATSNL allows the use of two different operating models as follows:

- **Trigger-driven operating model:** In this model, wireless sensor nodes sense the environment and wake up the rest of the nodes once an event is detected.
- **Schedule-driven operating model:** In this model, sensor nodes are directly driven by their processors so that the processors wake up to sample the sensors according to a predetermined schedule [8].

Common parameters of the simulation are as follows:

- Inter-arrival rates of events: 1 hour - 1 day
- Duration of events: 2 s
- Duty period: 20 s
- The ratio between active period and the full active/dormant period: 0.1 - 1
- Radio TX data rate: 256 Kbps
- Data size: 2 Kbyte
- Unit packet size: 128 bytes
- Header size of packets: 12 bytes

In this simulation, the lifetimes of telos [9] and imote2 [10] sensor nodes for 0 dBm and -25 dBm transmit powers are examined in order to analyze the effect of transmit power on node lifetime. The specifications of Texas Instruments CC2420, the transceiver used in imote2 and telos motes, are listed in Table 1. Fig. 2 shows the results of the simulation. The results of the simulation studies show that lifetime performances of telos nodes are better than imote2 nodes. Another result of this study is that predicted lifetime of sensor nodes can be improved by reducing transmission power. On the other hand, reducing transmission power reduces transmission range of all nodes. Thus balancing the trade-off between node lifetime and connectivity is necessary.

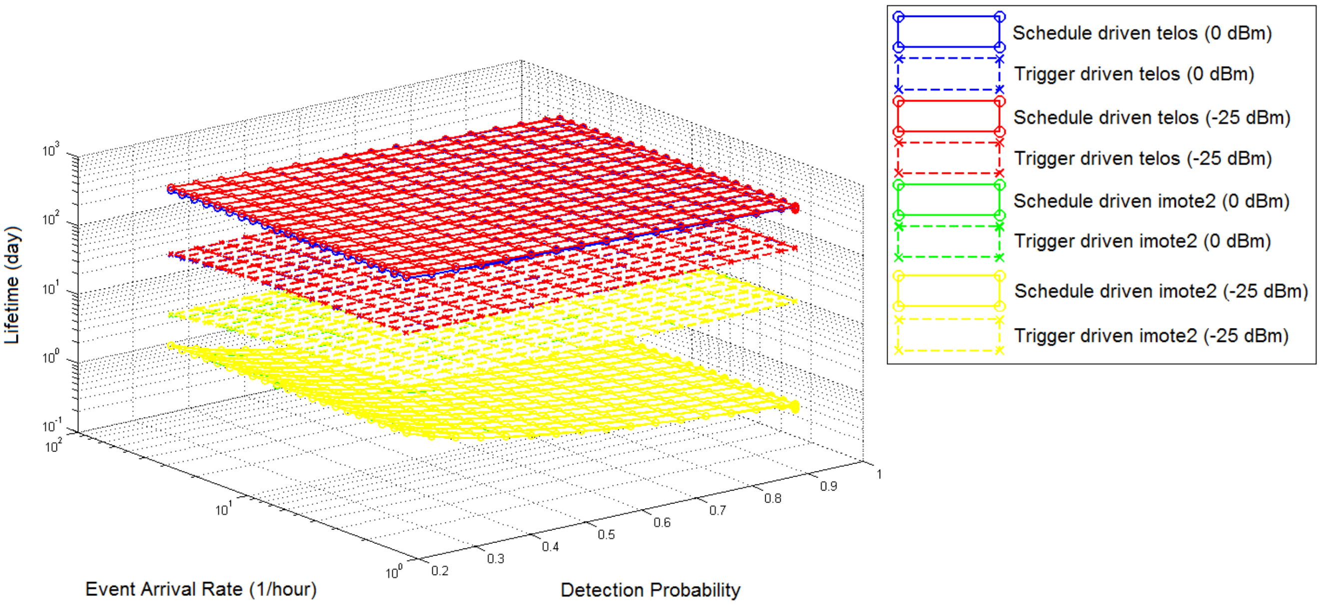

Fig. 2. Lifetime performances of imote2and telos nodes for 0 dBm and -25 dBm transmit powers for schedule-driven and trigger-driven operating models

Table 1. The specifications of TI CC2420 transceivers [7]

Standard	IEEE 802.15.4
Radio frequency (GHz)	2.4
Data rate (Kbps)	250
Supply voltage (V)	2.1 - 3.6
TX max (mA/dBm)	17.4 / 0
TX min (mA/dBm)	8.5 / -25
RX (mA)	18.8
Sleep (μA)	0.02
Startup (ms)	0.3 - 0.6
Modulation	O-QPSK

3.2. Localization and Navigation of UAVs

Localization and navigation are complementary processes. Unmanned ground/air vehicles must first localize themselves in order to navigate. Navigation can be described as the process of moving from a starting point to a destination. Localization can be described as the process used by unmanned vehicles/robots to calculate their positions through information gathered from sensors [11, 12]. To operate in dynamic environments, unmanned vehicles/robots need to acquire knowledge through perception by the use of available internal and external sensors [12, 13]. Therefore the localization and navigation system of unmanned vehicles/robots require a particular combination of internal and external sensors.

3.2.1. GPS and IMU integrated EKF based localization and navigation system

The localization and navigation system used in this study is based on EKF. The EKF algorithm uses Global Positioning System (GPS) and Inertial Measurement Unit (IMU) measurements received from the UAV. GPS and IMU sensors are common in almost all type of UAVs. Hence these sensors are preferred. Despite their advantages such as long time stability and being standalone sensors which provide absolute information of speed and position, GPS receivers cannot be used alone for navigation systems since they have low sample rates and require an open view of the sky to acquire signals which may not be possible in urban areas. In addition, they may give inaccurate results due to atmospheric effects. If more than four GPS satellites are observed, then there is a corresponding increase in the accuracy of GPS measurements. Another problem in urban areas is that tall buildings and skyscrapers constitute a problem for the navigation of UAVs [15].

In the proposed system, an overall model of the system is shown in Fig 3, the advantages of IMU and GPS receivers are combined in order to deal with the limitations of both sensors.

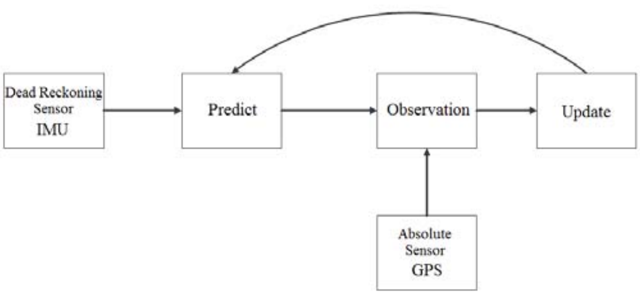

Fig. 3. GPS and IMU integrated EKF based localization and navigation system

In this system, an IMU is used as the dead reckoning sensor and keeps the track to an actual position, velocity and attitude with the aid of the GPS receiver. Information received from the IMU sensor is used to drive the kinematic representation of the UAV. A GPS sensor is used to minimize the errors caused by the IMU sensor.

3.2.2. The accuracy of navigation and localization systems and related simulations

In the literature, there are several approaches to evaluate the performance of navigation and localization systems. Most benchmarking approaches used to evaluate SLAM strategies use metrics which rely on global reference frames to compute the error. The evaluation approach used in this study is based on the estimated trajectory of a robot/unmanned vehicle. In this respect, the difference between the absolute ground truth pose and the estimated pose is computed by using the mean squared error (MSE) and this measurement over all ground truth points in time is referred as the absolute trajectory error (ATE) [14]. ATE is calculated by:

$$error = \frac{1}{N_{GT}} \cdot \sum_{i=1}^{N_{GT}} \sqrt{(x_i - \tilde{x}_i)^2 + (y_i - \tilde{y}_i)^2} \tag{1}$$

where N_{GT} is the number of ground truth measurements. x_i and y_i represent real position in Cartesian coordinate at step i. $\tilde{x}_i$ and $\tilde{y}_i$ represent estimated position in Cartesian coordinate at step i.

As it is well-known, SLAM accuracy depends on several factors such as sensing range, vehicle speed, frequency of observations and frequency of odometry readings. In this study, the results of a set of EKF-based SLAM simulations conducted using MATLAB, one of the simulations are shown in Fig. 4, are given to show the effect of vehicle speed on ATE. Nearest Neighbor (NN) data association algorithm is used by the EKF-based SLAM application. Table 2 lists the results of the simulations. It can be seen that SLAM accuracy decreases when the speed of an unmanned vehicle increases.

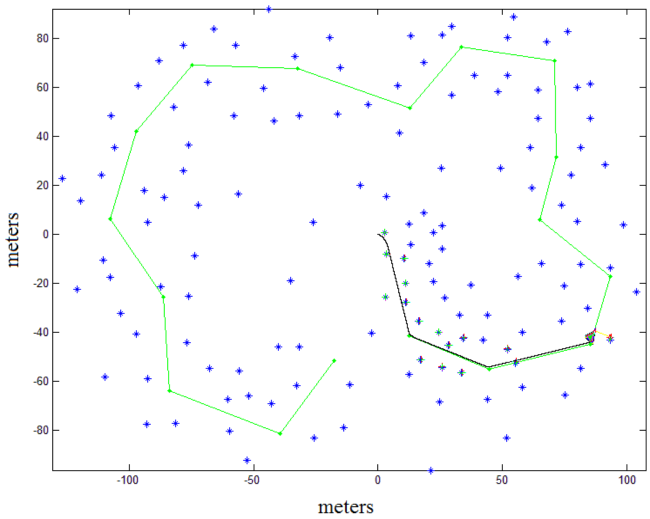

Fig. 4. EKF-based SLAM simulations used to evaluate the effect of vehicle speed on ATE

The results of the simulation studies show that unmanned vehicles/robots can localize and navigate themselves successfully using their sensors and priori maps. As listed in Table 2, increasing vehicle speed results in higher ATE and less accuracy. This necessitates the balancing of the trade-off between vehicle speed and ATE.

Table 2. ATE with different speeds

Observation range (m)	Time interval between odometry readings (s)	Time interval between observations (s)	Speed (m/s)	ATE (m)
30	0.05	0.5	0.3	0.251
30	0.05	0.5	1	0.853
30	0.05	0.5	3	2.901

3.2.3. USARSim based simulations

To show the localization and navigation performance of an UAV, the results of simulation studies conducted using USARSim and Visual C++ 2010 are given. USARSim is a simulation platform based on the popular Unreal Tournament (UT) game engine and serves both as a general purpose research tool and as the basis for robot competitions [16]. USARSim includes several types of commercial, non-commercial and research robots and environments. The methods described in this paper are aimed at developing an EKF-based navigation system via the integration of a GPS receiver and an IMU. To do this, firstly, an interface to control the robot in USARSim has been created. The control application which runs an EKF-based SLAM algorithm interfaces with the USARSim server, receives input from GPS and IMU sensors of the UAV and sends commands to the UAV. Communication with the USARSim server has been realized through port 3010.

Fig. 5. Simulated AirRobot

In the USARSim based simulation studies, a quadrotor helicopter, AirRobot, has been used. AirRobot is a four-rotor electrical helicopter with flight stabilization control [17]. AirRobot is used for many different purposes including, exploration, observation, documentation, and measurement. The simulated AirRobot flying by following a given trajectory in the simulations is shown in Fig. 5. In USARSim, USARBot.AirRobot class is used to represent an AirRobot. By default, in USARSim, the AirRobot is equipped with one tilt-only color camera. The proposed method is based on the use of GPS and IMU measurements to localize and navigate the AirRobot. Thus, a GPS receiver and an IMU have been placed on it. Also, an altitude sensor and a magnetic compass have been placed on it. To do these, GPSSensor.uc, IMU.uc, AltitudeSensor.uc and MagneticCompass.uc class files have been used. The GPS sensor finds the current AirRobot position in meters and converts it to latitude and longitude. The IMU sensor provides three sets of values such as x,y,z accelerations in m/sec^2, pitch, roll and yaw angles in rad and pitch roll and yaw accelerations in rad/sec^2. The altitude sensor provides relative altitude in m (altitude with respect to initial spawn location) and absolute altitute in m (relative altitude + above sea level) [18]. The GPS sensor has been placed at (0,0,2). The main problem with using a GPS sensor in USARSim is the mapping of a virtual location to a real one since USARSim worlds do not inherently have a GPS coordinate associated with them. Among the alternative methods to define a GPS reference point, editing the USARBot.ini file and adding ZeroZeroLocation inside the GPSSensor section have been preferred. The INS sensor simulates a physical INS sensor by using angular velocities and distance traveled.

Since UAVs will follow a predetermined trajectory to collect meter readings from smart meters over wireless links based on ZigBee in the proposed system, only position and heading errors from the real trajectory have been calculated without applying altitude control. Also, roll, yaw and pitch angles have not been estimated. Trajectory errors from the East and North are shown in Fig. 6 and Fig. 7 and heading errors are shown in Fig. 8. Only first 350 seconds of the simulation are shown in the figures. Table 3 lists comparative evaluations of IMU-based and GPS-IMU integrated navigation and localization methods. When calculating the trajectory errors and the heading errors, the filter outputs have been compared with the ground truth values obtained from USARSim.

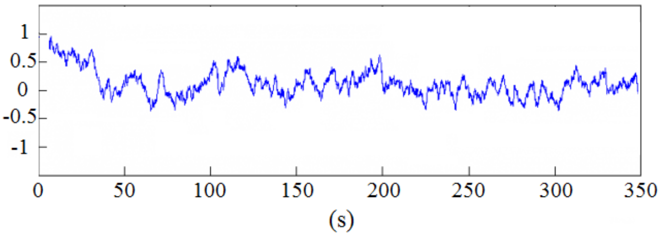

Fig. 6. Trajectory errors - East (m)

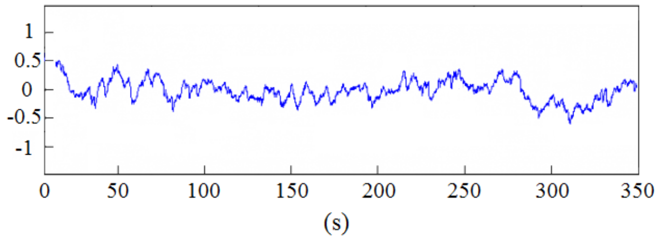

Fig. 7. Trajectory errors –North (m)

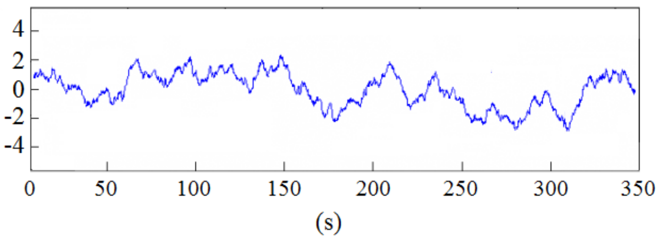

Fig. 8. Trajectory errors - heading (°)

Trajectory errors of the AirRobot are less than 0.39 m for longitude and latitude as listed in Table 3. Considering the trajectory errors, it can be concluded that UAVs can navigate and localize themselves successfully at the customer premises by using the proposed system when they are loaded with priori maps and waypoints.

Table 3. Comparative evaluation of IMU-based localization and GPS-IMU integrated localization methods

Overall mean value of errors	IMU-based	GPS-IMU integrated	Improvement (%)
Longitude (m)	0.861	0.387	55.052
Latitude (m)	0.741	0.364	50.877
Heading (°)	2.9	1.7	41.379

All simulation environments have some limitations and it is not feasible to rely on the results of simulation studies alone. Hence, in addition to the simulations, field tests with a prototype autonomous hexarotor shown in Fig. 9 are in progress. Since the UAV runs Robot Operating System

(ROS) [19] on Ubuntu, the application is being developed using ROS. Main specifications of the hexarotor are as follows:

- Embedded x86 computer with an Intel ATOM 1.6GHz CPU
- ARM 32bit controller
- Hokuyo URG04-LX indoor laser scanner (scanning range 4 m and 240°)
- Pointgrey USB color camera
- WiFi module
- ZigBee module
- Ultrafast IMU (1 kHz)
- Fast GPS module (4 Hz)
- GPS based position hold
- Attitude and position control
- Altimeter

Fig. 9. Autonomous hexarotor

4. Conclusions

This paper introduces the use of unmanned aerial vehicles for automatic meter reading applications and investigates its potential advantages and associated design challenges. This approach eliminates the need for installed wired/wireless network infrastructures and can be integrated to existing AMR systems. Thus this approach is especially suitable for AMR systems where there are several subscribers dispersed over a wide region. The results of simulation studies are given to show the effectiveness of the proposed approach. Field tests with a prototype hexarotor are in progress.

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