Cooperative Networked Control of Unmanned Air Vehicles

A Study of Quad-Rotors in a Smart Building Context

ISAK TJERNBERG
JONAS LINDBERG
KARL HANSSON

Bachelor’s Degree Project
Stockholm, Sweden May 2011
Cooperative Networked Control of Unmanned Air Vehicles

Isak Tjemberg  
Email: isaktj@kth.se

Jonas Lindberg  
Email: jonasl5@kth.se

Karl Hansson  
Email: karlhan@kth.se

Abstract—In recent years the interest and development of smart buildings has increased. One area that is still yet relatively unexplored is how unmanned air vehicles (UAVs) can be used in smart buildings. This report has approached the question of whether UAVs can have a use in smart buildings or not. In order to fully answer this question studies of the UAV best suited for smart buildings, quad-rotors, have been done. Even though the choice of UAV is task dependent, we found that quad-rotors are versatile and thus best suited for most applications. Furthermore to understand its benefits and limitations, modelling of quad-rotors will be presented. In experiments, successful autonomous flights with a quad-rotor have been realized using the theoretical model mentioned above. If the development of new technology, such as sensors and materials, continue at its current pace it is expected to see widespread applications with UAVs in smart buildings within a few years.

I. INTRODUCTION

Smart buildings that are aware of the actions inside them and that can respond to events where once considered futuristic and far fetched. Today the amount of electrical apparatuses in homes and buildings are increasing day by day. With this development the vision of self controlling smart buildings is coming closer. So what is a smart building then? A smart building uses networked sensors and control systems to control the behaviour of different systems within the building. This makes it possible for these control systems to anticipate and accommodate the needs of the inhabitants and users. Some examples may include controlling indoor heating or cooling depending on the expected number of users during the day, the weather forecast, etc. Other examples include turning off the lighting in the building when nobody is present, fall injury detection [1], burglary prevention or alerting the building maintenance crew when something is malfunctioning.

By efficiently planning and coordinating activities within the building both energy consumption for the individual systems as well as time consumption and standard of living for the users of the building can be improved. The market for smart buildings is still small mainly due to large initial costs. However, many companies expect a rise of the demand of this product. This is for example what IBM has to say about the importance of smart buildings:

"In the U.S., buildings consume 70% of all electricity, compensation to 50% of which is wasted. Lights blaze and air conditioners hum in empty offices at night, and lawn sprinklers turn on even during a rainstorm. Commercial buildings lose as much as 50% of the water that flows into them. By 2025, buildings will be the single largest energy consumers and emitters of greenhouse gasses on our planet. [...] Smart buildings can reduce energy consumption and CO₂ emissions by 50% to 70% and save 30% to 50% in water usage.” [2]

This paper will investigate the uses of Unmanned Air Vehicles (UAVs) in a smart building. There are many different applications for UAVs but the one that feels closest at hand in a smart building is surveillance and security, hence this will be the focus of this report. In order to fully understand the opportunities, benefits and disadvantages of using UAVs in a smart building a variety of topics will be approached and analysed. First a comparison between different UAVs will be made to conclude which types of UAVs are suitable for which tasks. Second the UAV that is found most suitable for the security and monitoring application, namely the quad-rotor, is investigated with further depth. This is done by examining the characteristics and providing a basic model and control of a quad-rotor. A variety of sensors that can be of use in quad-rotors are also examined. Finally some aspects of networked control of multiple UAVs and other possible elements within a smart building are discussed. Some experimental results that were done using a commercial quad-rotor are then presented and discussed.

The goal of this report is to give an overview of the use of UAVs in a smart building. One type of UAV, quad-rotors, will be investigated in greater depth. However no great depth in any of the subjects should be expected, rather an overview to examine the validity and challenges of this application.

In the first part of this report a comparison of different kinds of UAVs will be made. Then a model and control for a quad-rotor will be presented. After that there is a section describing appropriate sensors and a network type to use on a quad-rotor. In the later parts of the report an application in which we believe UAVs could be used in is proposed. Lastly we present how our practical experiments was conducted, also results and conclusion will be discussed.

II. UNMANNED AERIAL VEHICLES

A. Advantages of Unmanned Aerial Vehicles

Stationary sensor nodes have a lot of advantages, they are cheap and reliable. However, they have a huge drawback which is that they will always have blind spots. This is due to the fact that they can only observe the area in which they are installed due to lack of mobility. To cover an entire building...
many stationary cameras must be used. If the building is large enough and it is important to get sensor data from all parts of the building, stationary sensor networks can be too expensive to have, due to the large number of sensors needed. Also, if things change in the building stationary sensors can be distracted, for example if a commercial sign is put in front of a camera it is useless unless it is moved. Therefore mobile cameras and other types of sensors are sometimes needed. Ground moving robots can be used to solve this issue. They, however, also have a big disadvantage. It is easy to imagine a ground robot moving around in a factory or a shopping mall being an obstacle for the people in the concerned building. UAVs can provide a solution for this problem where stationary and ground moving robots fail. UAVs are not sensitive to the changes in the building and if the ceiling height is sufficient (which is often the case in for example, airports, shopping malls and factories) UAVs can operate without disturbing anyone.

In recent years big developments in material, electronics and wireless networks have been done. This has enabled UAVs to evolve into a useful tool in smart buildings. Because of this relatively new progress in the field of UAVs, the market have not quite yet been keeping up. This young market have a large potential and huge expectations for tomorrows UAVs in smart buildings have stimulated companies and researchers all over the world to continue the development of small UAVs.

B. Comparison of Unmanned Air Vehicles

There are a variety of UAVs and they have different properties which yields different advantages and disadvantages. In this section a comparison between different kinds of UAVs will be made in order to find out which one is best suited to use in a smart building.

As foundation for this study, a paper by Bouabdallah, et al has been used [3].

There are two main types of UAVs, LTA (Lighter Than Air) and HTA (Heavier Than Air). These two types can also be divided into two subcategories, namely motorized and non-motorized. Here are some examples of vehicles in the different categories, pictures of the examples can be found in Figure 1.

- Lighter Than Air
  - Motorized
    * Blimps (Figure 1 (a))
    * Zeppelins (Figure 1 (b))
  - Non-Motorized
    * Balloons (Figure 1 (c))
- Heavier Than Air
  - Motorized
    * Rotor-crafts (Figure 1 (d))
    * Air-planes
    * Birdlike (Figure 1 (e))
  - Non-Motorized
    * Gliders (Figure 1 (f))

The difference between Zeppelins and blimps is that since blimps does not have a metal skeleton support it is more lightweight but less stable. Birdlike crafts have moving wings that flap in contrast to normal air-planes that have fixed wings.

To find the UAV that is best suited for indoor usage we will rate some important criteria for usage in a smart building. Each criteria is rated from one to three, where three is excellent and one is poor. We decided only to compare air-planes, rotor-crafts and blimps. Since they are, from our point of view, the top three motorized candidate UAVs.

As seen in Table I rotor-crafts fulfil more of our desired criteria than the other types of air-crafts. Therefore we conclude that rotor-crafts are appropriate for indoor applications. The main reasons are: They can fly both slow and fast, it is easy to control them in all directions and they can be built small enough to be used indoors. Rotor-crafts, however, powered by batteries cannot sustain flight for long periods of time. Though this is not a major disadvantage since buildings often have electricity and therefore can easily recharge the UAV when it is needed.

Blimps are great for surveying big areas where speed or range is not of great importance, for example a large parking lot. Air-planes on the other hand are suitable to survey larger areas, for instance air-planes are good as military reconnaissance planes or for forest fire reconnaissance.

### III. Properties of a Quad-rotor

The quad-rotor has typically two perpendicular pairs of rotors rotating in opposite directions. This is good because it makes it easy to manoeuvre. Since each pair of rotors creates a torque on the quad-rotors body directed opposite to the propeller rotation, the torque created by one pair of rotors can be compensated by the other pair. This way the UAV can for example tilt, rotate and control its height independently of each other which is impossible with less then four rotors (given that the axis of the rotors are fixed). For example, a regular helicopter with a horizontal and a vertical rotor cannot move forward without tilting the rotor at the top of the vehicle. Because the quad-rotor have very few moving parts it can be built very robust and it is able to perform all the manoeuvres that an indoor UAV might need.

A sketch of a quad-rotor seen from above can be found in fig. 2. One thing to note here is that the $x$, $y$ and $z$-axes are
fixed in the quad-rotors own coordinate system, if the quad-rotor rotates the axes move with it. Again, referring to fig. 2, if the quad-rotor rotates 90° clockwise, the $x$-axis would now be directed to the right in the image, and the $y$-axis to the top. This simplifies the modelling of the quad-rotor since it is always possible to know which way is forward, to the side and so on. It is important to keep in mind that when navigating in an outer coordinate system (the real world), the transformation between the outer coordinate system and the quad-rotor’s coordinate system would have to be known in order to understand how the quad-rotor is positioned in the real world. This transformation between coordinate system changes over time as the quad-rotor moves about.

A. Basic Maneuvers

A description of how the three basic movements that a quad-rotor can make are achieved will be described in this section. They can also be combined and executed at the same time [4].

1) To do the simple up or down manoeuvring all the rotors of the quad copter rotate at the same angular velocity each generating equal thrust upwards. If the sum of all thrusts is less than the gravitational force the UAV will descend and vice versa.

2) To rotate left or right the sums of torques should not be zero but the thrusts should be equal to the gravitational force. Since rotor 1 and 3 turn clockwise they create a counter-clockwise torque on the UAV and rotor 2 and 4 create a torque in the clockwise direction. This property can be used to turn the UAV without tilting it. So if engines 1 and 3 have greater angular velocity than engines 2 and 4 the UAV will turn counter-clockwise and vice versa.

3) In order to tilt forward with a quad-rotor the sum of all thrusts from the propellers should be equal to the gravitational force, but rotor 3 and 4 needs to have a greater angular velocity than 1 and 2. The quad-rotor will then tilt forwards and start to accelerate. Since the sum of torques around the $z$-axis is zero the UAV will not turn, it will just tilt forward around the $y$-axis.

IV. Modelling A Quad-Rotor

In order to control a quad-rotor, we need to model its movements as a function of the thrust from its engines and the tilt. A number of simplifications are made in order to make a linear model that is easy to understand. For example air resistance is ignored as well as gyroscopic effects. Variables are defined as follows.

$$\theta = \text{Pitch} \quad \phi = \text{Roll} \quad \psi = \text{Yaw}$$

See figures 3, 4 and 5 to get a better idea of these angles. As described in [5], an equation of force can be written as follows

$$\vec{F} = -mg\hat{e}_z + \sum_{i=1}^{4} \vec{T}_i$$

where $\vec{T}_i$ is the force from each rotor, $mg\hat{e}_z$ is the mass $m$ multiplied with the gravity constant $g$ in the $z$-direction. Assuming that the pitch and roll are both small, the small angle approximation can be used. In practice this means that $\sin(\theta) \rightarrow \theta$ and $\cos(\theta) \rightarrow 1$ when $\theta$ is small. With this approximation the equation can be rewritten in vector form as

$$\vec{F} = m\ddot{\vec{a}} = m \begin{bmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{z} \end{bmatrix} = \begin{bmatrix} \theta \\ -\phi \\ 1 \end{bmatrix} T + \begin{bmatrix} 0 \\ 0 \\ -mg \end{bmatrix}$$

(1)

where $T = |\sum_{i=1}^{4} \vec{T}_i|$. A quad-rotor can not only move in the $x$-, $y$- and $z$-directions but also rotate around all these axes. In order to completely understand how a quad-rotor behaves an equation of the angular momentum is also needed. As explained in [5] a non-linear angular momentum equation is given as

$$\vec{M} = I\ddot{\vec{\omega}} + \vec{\omega} \times I\vec{\omega}$$
Figure 3. The grey quad-rotor shows the old position and the black quad-rotor its new position. The angle $\phi$ between the two quad-rotors is defined as the roll. $\phi$ is positive according to the right hand rule. Roll is used to move the quad-rotor sideways.

Figure 4. The grey quad-rotor shows the old position and the black quad-rotor the new position. The angle $\theta$ between the two quad-rotors is defined as the pitch. $\theta$ is positive according to the right hand rule. When the quad-rotor pitches it moves forward or backwards.

Figure 5. The grey quad-rotor shows the old position and the black quad-rotor the new position. The angle $\psi$ between the $x'$-axis and the $x$-axis is defined as the yaw. $\psi$ is positive counter-clockwise. When yawing the quad-rotor rotates around the $z$-axis.

Figure 6. Simple model of our quad-rotor. It has four point masses $m_1$ at the distance $l_1$ from the $x'$- and $y'$-axis. It also consists of a rectangular parallelepiped with continuous mass distribution $\rho$ with side lengths $l_2$, $l_3$ and $l_4$.

By continuing equation (2), this is described as

$$\bar{M} \approx I \dot{\omega} = \begin{bmatrix}
I_x \ddot{\phi} \\
I_y \ddot{\theta} \\
I_z \ddot{\psi}
\end{bmatrix}$$

(3)

here $l$ is the length from the $x'$- or $y'$-axis to the center of a rotor, in this case equal due to symmetry. $K_r$ is a constant relating the thrust from one engine to an angular momentum. A similar model was also derived in [5].

V. CALCULATING MOMENT OF INERTIA

An expression of a quad-rotors moment of inertia about each axis will here be derived. A simplified model of a quad-rotor can be found in Figure 6. The quad-rotor is approximated by a box with a continuous mass distribution, of density $\rho$, and also four point masses representing the engines.

The moment of inertia of this simplified model of a quad-rotor can be calculated as follows.

$$I = \sum_{i=1}^{4} m_i r_i^2 + \iiint_V \rho(\vec{r}) d(\vec{r})^2 dV$$

Where $r_i$ is the shortest distance from the axis to the point mass $m_i$. The integral is over the entire volume $V$ of the quad-rotor volume. Similarly $d(\vec{r})$ in the integral is an expression for the distance between the axis and an infinitesimal mass point with mass density $\rho(\vec{r})$. These are the results from each corresponding axis:

$$I_x = 4m_1 l_1^2 + \frac{8\rho V}{3} (l_3^2 + l_4^2)$$
\[ I_y = 4m_1 l_1^2 + \frac{8\rho V}{3}(l_2^2 + l_3^2) \]
\[ I_z = 8m_1 l_1^2 + \frac{8\rho V}{3}(l_2^2 + l_3^2) \]

VI. CONTROLLING A QUAD-ROTOR

As has already been said, the only way to control the motion of a quad-rotor is to adjust the thrust from each of its rotors. In a quad-rotor it is important to use a well functioning controller algorithm in order for the UAV to behave as desired.

A traditional PID-controller is given on the form
\[ u(t) = K \left( e(t) + T_d \frac{\dot{e}(t)}{T_1} + \frac{1}{T_i} \int e(t) \, dt \right) \]  
(4)

where \( e \) is the difference between the desired value of the controlled variable and its actual current value, \( K \) is a general gain for the system and \( T_d \) is a parameter relating the influence of \( e \) to \( u \). Similarly \( T_I \) relates the integral part to \( u \). The last term in eq. (4) has the effect of reducing the static error to zero. \( u \) is here a new signal into the system (in the case of a quad-rotor it will be thrust).

Assume a quad-rotor is equipped with sensors to measure pitch, roll, yaw and height \((\theta, \phi, \psi, z)\), and that we have desired angles and height as \( \theta_d, \phi_d, \psi_d \) and \( z_d \). The control errors can now be described as:

\[
\begin{align*}
  e_\theta &= \theta_d - \theta \\
  e_\phi &= \phi_d - \phi \\
  e_\psi &= \psi_d - \psi \\
  e_z &= z_d - z
\end{align*}
\]

Each of these errors should, by adjusting the thrusts from each rotor, be reduced to zero. As described below, the four errors give four control signals on how the quad-rotor should adjust the thrusts of its engines. These signals can then be super-positioned before sent to the engines. Some of these signals will be negative, but when taking the sum of all the signals the result should be positive as a negative thrust from an engine makes no sense (propellers don’t generate thrust when running backwards).

So, in summary, thrust \( T_1 \) is determined as the sum of \( T_1 \) from height, pitch, roll and yaw control respectively. The same logic applies to \( T_2, T_3 \) and \( T_4 \).

A. Height Control

The height, \( z \), of the quad-rotor is only affected by the total thrust from the rotors as can be seen from equation (1).

\[ \ddot{z} = \frac{T}{m} - g \]

Thus, for height control, \( u \) given in eq. (4), with \( e = e_z \), is the total thrust, which should be divided equally to each rotor.

B. Pitch Control

The angular momentum equation (3) provides an expression for the angular acceleration of the pitch
\[
\ddot{\theta} = \frac{l}{I_y}(-T_1 - T_2 + T_3 + T_4) \]
(5)

As seen here the control of the pitch of the quad-rotor is more complicated than height control since it involves different thrusts to each engine. The labelling of the engines and thrusts are those seen in figure 2. According to eq. (5) higher thrust from rotors one and two than from three and four would give a negative angular acceleration of the pitch. This means the quad-rotor will tilt more backwards. In order to achieve different thrusts from different engines the output \( u \) produced by eq. (4) must be post processed before the signal is sent to the engines. In the case of only controlling pitch, the engine pair one and two can be controlled as one and similarly engines three and four also have the same thrust.

To give some more details on this matter, assume the quad-rotor is positioned at an angle \( \theta < \theta_d \) which means the quad-rotor should tilt forwards to reach the desired angle \( \theta_d \). The pitch controller senses this and according to eq. (4) with \( e \) replaced by \( e_\theta \) it calculates a positive control signal \( u \). For the quad-rotor to start tilting forwards, a larger control signal should be sent to engines three and four than to one and two. This is where the post processing of the control signal \( u \) is needed. To achieve the desired behaviour, the post processing could be switching signs on the signals sent to engines one and two compared to the signal sent to three and four. This way the sum of all torques equals zero except around the \( y \)-axis and thus only pitch is affected.

C. Roll Control

As earlier stated, the dynamics of the roll of a quad-rotor is described by
\[
\dot{\phi} = \frac{l}{l_y}(T_1 - T_2 - T_3 + T_4) 
\]

The behaviour is similar to that of the pitch, \( \theta \), with the difference being which rotor pairs cooperate to adjust the angular acceleration. Following the same reasoning as in subsection VI-B one finds that here the control signal to engines two and three should be reversed compared to one and four.

D. Yaw Control

Eq. (3) states that the yaw of the quad-rotor depends on the thrusts of the engines as
\[
\dot{\psi} = \frac{K_r}{l_z}(T_1 - T_2 + T_3 - T_4) 
\]

Here it is the control signal to engine two and four which should be post processed by switching signs.
E. Position Control

When controllers for pitch and roll have been designed, controllers for x- and y-position of the quad-rotor can also be created. When having desired values for x- and y-position, $x_d$ and $y_d$, the position errors are

$$e_x = x_d - x$$
$$e_y = y_d - y$$

This means that the quad-rotor must know where it is positioned for each point in time, otherwise no errors can be calculated. Assuming that this is possible (perhaps by getting position updates from an external sensor system) a controller which outputs an angle for how the quad-rotor should tilt can be designed. A PD-controller is a suitable choice as it gives a quick response time while keeping the overshoot low. An integral part could be added to remove steady state errors occurring when the desired position is changing in time.

Two controllers are needed, one in the x-direction and one in the y-direction. The differences of these controllers depend only on the differences between the moment of inertia of the quad-rotor around the y- and x-axis. Since the controllers will only differ in parameter values, only the controller in x-direction is discussed here. A PD-controller is on the form

$$u = P e_x + K_d e_x$$

In this case $u$ is no longer a thrust but instead the angle $\theta$, which is to be held by the quad-rotor. In the case of the controller being in y-direction, $u$ would instead be the angle $\phi$. This is assuming that the x- and y-axis are directed according to the quad-rotor as seen in figure (2). This controller can now be combined with the controller for setting the pitch or roll of the quad-rotor. The position controller calculates a new angle to be held by the quad-rotor, this angle is then sent as input to the angular controller which adjusts the angle of the quad-rotor accordingly. As a result from the quad-rotor now tilting it will start to move. The new position is sent as feedback to the position controller which calculates a new angle and so on. A schematic figure of the controller is shown in figure 7.

F. Digital Implementation

When using the earlier designed controllers for height, tilt and x- and y-position they will in practice be implemented digitally in a computer on board the quad-rotor or on a computer communicating with the quad-rotor. When implementing a controller digitally there are several issues to address. One is that the derivative part of the controller must now be approximated by a difference equation, and also the integral must be approximated by a sum. As discussed in [6] the PID-controller is given as

$$u(t_k) = P(t_k) + D(t_k) + I(t_k)$$

where

$$P(t_k) = K e(t_k)$$

$D(t_k)$ is the derivative part, $I(t_k)$ is an expression for the integral and $e(t_k)$ is the control error. When a controller contains a derivative part and uses digital sensors for control feedback it may be sensitive to measurement noise from the sensors. If there is a sudden noise spike, the derivative of the signal will be large and so also the control output. In order to reduce the sensitivity of the controller, as said in [6], one could use a first order filter to adjust the derivative part. In continuous time this would mean the derivative part looks like

$$D = \frac{K T_d s}{1 + s T_d /N}$$

The constant $T_d / N$ can then be tuned to make the noise have little effect on control performance. Noise is usually high frequency, for which the derivative part can be approximated by $D \approx K N$. This means the derivative action is only present for small enough frequencies and at higher frequencies the noise will not be derived, only multiplied by a factor $K N$. This first order filter is also known as a low pass filter as it lets through those signals with a low enough frequency without affecting them. The value of $T_d / N$ is affecting the cut-off frequency of the filter, the cut-off frequency is the frequency at which the signal is reduced by a factor of 3 dB (in other words the signal is reduced by a factor of two). Choosing a larger value of $T_d / N$ lowers the cut-off frequency while reducing $T_d / N$ increases the cut-off frequency. In order to implement a derivative controller digitally, the control signal must be derived with numerical methods. To approximate a first-order derivative one could use Tustin’s formula, which states that

$$\hat{u}(t) \approx \frac{2}{T} (u(t) - u(t - T)) - \hat{u}(t - T)$$

where $T$ is the time between measurements of the signal $u$. [6] It is important to note that the formula takes into account what the derivative was at the earlier time step, and then adjusts accordingly. By discretizing the time variable in steps of $T$ with index $k = 0, 1, 2, 3, \ldots$ the formula can be written as

$$\hat{u}(t_k) \approx \frac{2}{T} (u(t_k) - u(t_{k-1})) - \hat{u}(t_{k-1})$$

According to [6] the derivative term in eq. (6) can with Tustin’s formula be written as

$$D(t_k) = \frac{2 T d_{\text{N}}} {2 T_d + N T} \left( 2 K T_d N \frac{y(t_k) - y(t_{k-1})}{2 T_d + N T} \right)$$

The integral part of the controller must also be approximated with numerical methods. This is done by simply adding together small area parts as time passes by. Mathematically this is expressed as

$$I(t_k) = I(t_{k-1}) + \frac{K}{T} \frac{e(t_{k-1}) + e(t_k)}{2} T$$

The formula can be interpreted as taking the last value of the integral and adding the area spanned by the error since the last sample. $T$ is the time between one sample and the next one.
The controller in eq. (6) can now be fully written as

\[ u(t_k) = Ke(t_k) + I(t_k - 1) + \]

\[ \frac{Ke(t_k - 1) + e(t_k)}{T} T + \]

\[ + \frac{2T_d - NT}{2T_d + NT} D(t_k - 1) - \]

\[ \frac{2KT_dN}{2T_d + NT} (y(t_k) - y(t_k - 1)) \]

Please note that \( T \) is here the sample time, or in other words the time between one measurement of the control variable and the next one.

VII. Sensors in a Quad-Rotor

In order to fly a UAV autonomously it needs to have multiple sensors that keep track of its position and movement. For complex UAVs such as a quad-rotors the sensors are extremely important since it is almost impossible for a human to control four rotors independently to make the UAV fly as desired. In this section we will focus on the different kinds of sensors that are commonly used in quad-rotors.

A. Gyroscopic sensors

Gyroscopic sensors are used by a UAV to measure how it is rotating with respect to its own coordinate system. Normally three gyroscopic sensors are used, one for each axis. The type of gyroscopic sensor most widely used today is the so called MEMS (microelectromechanical systems) gyroscopes. A more classic gyroscope consists of a rotating disk, however these tend to take up more space and are also in comparison expensive and heavy. Therefore these are not as suitable for use in a small UAV as the MEMS equivalent. MEMS gyroscopes on the other hand are small silicon chips that are cheap, light and small. [7], [8]

If a current is applied over certain materials they start to vibrate at a given frequency. A vibrating mass will when rotated tend to stay in the plane in which it vibrates. The chips are designed so when at rest the mass vibrates in a certain direction, for example the \( x \)-direction. When the mass is rotated along the \( z \)-axis a Coriolis force along the \( y \)-axis will act on the mass. This force can be measured and then the speed of rotation can be derived. [9]

Gyroscopic sensors only measure the current change rate of angle, the speed of the rotation. In order to get the absolute angles of the UAV the output of the gyroscopic sensors should be integrated. This is not unproblematic as the noise of the sensor is also integrated. In turn this can cause the angle to drift, in other words having a constantly growing error, even if the UAV is not moving at all. [4]

B. Accelerometers

Accelerometers measures, as the name implies, how the device accelerates. This can be integrated to give the speed of the device. It is common to have three accelerometers on the body frame of the UAV, one for each direction.

A popular way of measuring acceleration is by mounting a mass in a fixed frame. When the sensor (and its frame) is accelerated the mass will due to inertia experience a force. In order to calculate the acceleration one must be able to measure the force performed on the mass during the acceleration. One could schematically view the sensor set up as a mass...
dampened by springs. These "springs" can be constructed in a number of ways, for example they can be made of a piezoelectric, a piezoresistive or a capacitive material. Just as in the case with the gyroscope the force can be measured and since the spring constant is known the acceleration can be derived [10].

C. Visual

The visual sensor, or in other words, a camera, has many uses. It can be used to identify objects and obstacles, the surroundings of the aircraft, measure distance, positioning and a lot more. However the versatility of the sensor or sensors greatly varies with the resolution, viewing angle and number of cameras. The cameras can both be used with a computer that automatically processes the images and takes appropriate action, or it can be transmitted to a remote operator or supervisor to give that person insight to the aircraft’s progress of the task or enable the operator to remotely control the craft.

Greater resolution allows for greater detail, but it also requires more computational power to process and higher network speeds to transfer the larger amount of data. An assessment of the task at hand must be done about what should be prioritized.

One way of determining the position of the UAV in a known environment is to have characteristic unique signs or tags at known positions in three dimensional space. Once these tags are spotted by the on board visual sensor the position of the aircraft can be determined with high accuracy. [11]

D. Ultrasound altimeter/telemeter

Ultrasound sensors can be used with UAVs to either measure the height above the ground or the distance to obstacles in the flight trajectory. The big advantage of using ultrasound sensors is that they are not very sensitive to the environment in which it is in. Unlike cameras, ultrasound sensors are not affected by for example weather or lighting conditions.

Ultrasound sensors works like a sonar. It sends out a pulse and then measures the time for it to echo back. Since the velocity of sound in air is known it is easy to derive the distance to the object that the sound reflected from. [12]

One problem with these sensors is that one can not always be certain that the ultrasonic pulse is reflected against the object of interest. If, for example, the ultrasound sensor is used to measure the height of the UAV, the ultrasound should be reflected against the floor of the building. If the UAV is flying close to a wall or another object, the sound might bounce against the wall or other object instead of the floor, providing a misleading reading of the height above ground.

E. Global Positioning System

A GPS basically works by measuring the time it takes for a signal the go from the GPS device to a geostationary satellite. Since the signal is travelling at approximately the speed of light the time measured can be related to a distance. Note that relativistic effects has to be taken into account. One satellite gives one distance which corresponds to a radius of a sphere on which the GPS device must be. By adding measurements from additional satellites more spheres are given and the accuracy of the position increases.

Since sensors like accelerometers and gyroscopes tend to drift over time, they are not very reliable over long periods of time. A Global Positioning System (GPS) sensor, however, can under some circumstances give the UAV its global coordinates with a precision of about ten meters. By using help systems and correction algorithms this error can be decreased to about one meter [13]. So if the UAV is to be used in a large building complex where it is not possible to have cameras or tags to give the global position of the UAV a GPS could be a suitable alternative. Note that the precision of a GPS device is often reduced when used indoors because the signal is in most cases unable to take the shortest route between the satellite and the transceiver.

Therefore, some problems arises when using GPS as the only means of positioning. The position can be unreliable if the sensor is indoors, if it is shadowed by tall buildings or something similar. The relative big error of up to around ten meters can also be a problem since higher accuracy is often desired when navigating in narrow spaces.

F. Other Sensors

These sensors mentioned above are of course not the only sensor types which can be used on a UAV in a smart building. The choice of what sensors to use are entirely based on the purpose of the task that the UAV have. Infra-red cameras can be used to detect heat if the purpose of the UAV is to monitor for example the spreading of fires. Sensors that detect radioactivity could be used to measure the spread of a radioactive cloud at disasters at nuclear power plants, and so on.

VIII. COMMUNICATION NETWORK IN A QUAD-ROTOR

Having more than one UAV performing a task, a network is needed to make each UAV able to communicate with each other. The structure of the network can be of different natures. For example a central server that handles the data from the group and makes the macro decisions on how to proceed can be used. Another method could be that the UAVs communicate directly with each other when they are in range.

The server method however gives the advantage that one unit is responsible for the big picture and can then take decisions knowing all of the parameters. However it can also be more prone to fail if the server crashes or has connection problems. A mix of several different solutions could be another good idea.

The amount of data that can be sent over the network is limited. Therefore care has to be taken of what should be sent. The data can be processed on board of the mobile units, however this will lead to more power consumption and require larger batteries or shorter range. If possible it can be an advantage to process the majority of data, such as image data, on the main server where low power consumption is not as important.
A. Wi-Fi

Since the reason for implementing a UAV to solve problems mainly is due to its mobility a wireless communication protocol is needed. There are many alternative protocols that could be used to send information wirelessly. It is wise to use an existing and well working infrastructure. Depending in what application different kinds of networks protocols are suitable. However since the UAV is to be indoors in large building complexes, the IEEE 802.11n-2009 (Wi-Fi) protocol is a good candidate. Wi-Fi is accepted as a standard wireless protocol for communication between computers. IEEE 802.11n have an approximated range of about 70 meters and speed up to 600 Mbit/s [14]. This is good enough to send all the interesting sensor data, including video, and instructions to several UAVs. If no video is to be sent, the demand on high transfer rates for the data is decreased. Then a less energy consuming protocol could be used such as ZigBee [15].

B. Encryption

The data sent over the network needs to be encrypted so unauthorized people do not get access to the information sent between the UAVs or to the server. Encryption is also important so that the expensive equipment is not hijacked and stolen or misused.

The encryption needs to be hard to break, while still keeping the UAV lightweight, cheap and energy efficient. Expensive and heavyweight computation circuits are preferably avoided. Therefore the encryption algorithm needs to be computationally cheap and yet very secure.

Advanced Encryption Standard (AES) is an encryption standard which was developed by Joan Daemen and Vincent Rijmen. The government of the USA considers it to be strong enough to encrypt classified documents [16]. The algorithm can be implemented in low-power hardware architectures [17] with relative low encryption/decryption time, making it possible to stream encrypted data.

C. Jamming

It is always possible to disturb any wireless transmission by adding noise to the frequency in which the wireless units communicate, this is called jamming [18]. If the disturbance noise is big enough it is impossible to sort out the data signal from the noise. The only way to defend against a jamming attack is to change to another transmission frequency.

Even though wireless systems are always fragile to jamming attacks the attacker reveals himself as soon he starts his attack. The attacker can then be found by triangulating where the attack comes from and then the attack can be terminated. Since this vulnerability exists it is a good idea to build your system so that it will not fail entirely if the communication between individual devices go down.

IX. PATH FOLLOWING

When performing a task with one or multiple UAVs it is desirable to have the crafts follow a set path through space. The path in question is here assumed to be already decided.

With the earlier position controller proposed a quad-rotor with a well known position can be sent to a specified point in the room.

Assuming the path to follow is a continuous curve in three dimensions, the curve could be approximated by a finite number of points connected with straight lines. The set of points, $P$, is given as

$$P = \{p_1, p_2, p_3, ..., p_k, ..., p_N\}$$

where each point, $p_k$, is a location in three dimensional space.

The number of finite points used to approximate the curve will affect how good the approximation is. A simple way of making a quad-rotor follow a path made up of distributed points would be to use the earlier designed position controller to send the quad-rotor to a point in the path and afterwards continuing to the next one. This algorithm would mean that the quad-rotor would slow down and almost come to a stop before arriving at a point in the path. The quad-rotor would then have to accelerate towards the next point, making the path tracking unnecessarily time consuming and tedious.

The performance with this solution is influenced by the number of points used to approximate the path. A larger number of points gives a large number of stops made by the quad-rotor when it is tracking the path.

A more effective approach would be to have the quad-rotor aiming for the next point in the path before coming to a halt at the first point. The method would be to form a sphere around each of the points in the tracked path, and when the quad-rotor has reached the edge of the sphere the target to track is switched to the next point in the path.

A good choice of the radius of each sphere would be one that keeps the quad-rotor up to reasonable speed (as little deceleration/acceleration as possible) while at the same time tracking the original path well enough. A trade-off between these aspects has to be made. This way of tracking a path would vary the speed at which the quad-rotor is travelling depending on how far away from the next point the quad-rotor is at the moment.

Another path tracking method is presented in [19], where a UAV is kept travelling at a constant speed and height. Thus the $z$-dimension of the path is removed and the quad-rotor is confined to travelling in the $(x, y)$-plane at a constant height. The method in [19] consists of creating a vector field for a known path to follow. The vector field will be only two dimensional since we are in the $(x, y)$-plane. The constructed vector field gives the desired direction of heading for the UAV at a given position in the plane. If the UAV keeps the heading given by the vector field the path will be successfully tracked. Creating the vector field for a given path is a topic on its own, but two examples of vector fields are shown in fig. 9, these where created in [19].

Of course, the more complex a path is the harder it will be to construct a matching vector field. However, many paths that are not to complicated can be more or less well approximated by a combination of lines and parts of circles, which have vector fields according to figure 9.
When using UAVs for monitoring and security applications it is beneficial to be able to track moving targets. These objects could either be moving on the ground or be other flying objects.

A. Targets on the ground

In the case of land moving objects, the UAV would preferably be equipped with a downwards facing camera. It will then be trying to stay on top of the target, at some fixed height. The height to be kept by the UAV is of course environment dependant, if the situation is set inside a building the height is obviously restricted by the ceiling of the building. However, in general, flying at a higher altitude is better as it gives the UAV a larger field of view of the ground.

Trying to keep a quad-rotor over a moving object by using images from a down facing camera is not entirely trivial. This is due to the fact that pitching or rolling the quad-rotor will affect where in the image the tracked object is located. In order to understand how the UAV is positioned in relation to the tracked object, the image data need to be fused with other types of sensor data describing the tilt of the UAV. In [20] a formula is presented which gives the position of the UAV in relation to the tracked object by combining information about the height of the UAV, the offset of the tracked object in the image and the tilt of the UAV.

\[\theta_c = \frac{i_x}{i_{x_{\text{max}}}} \alpha\]
\[\phi_c = \frac{i_y}{i_{y_{\text{max}}}} \beta\]
\[dx = h \tan(\theta + \theta_c)\]
\[dy = h \tan(\phi + \phi_c)\]

In these formulas \(i_x\) is the offset (in pixels) of the tracked object in the image, \(i_{x_{\text{max}}}\) is the maximum pixel in the \(x\)-direction (measured from the center of the image) and \(\alpha\) is the angle of view of the camera. The angle of view is here measured as how wide the camera can see, in angle from the center of the image to one edge. \(\theta_c\) is thus the angle from the cameras directional axis to the tracked object. The same reasoning is applied to \(\phi_c\), but in \(y\)-direction instead, where angle of view is now \(\beta\). Furthermore, \(h\) is height of the quad-rotor and \(\theta\) is pitch while \(\phi\) is roll. For better understanding of these formulas, please refer to figure 10.

The calculated offsets from these formula provides a better understanding of the relative position of the quad-rotor to the tracked object.

Given these offsets a PID-controller can be designed to keep \(dx\) and \(dy\) at zero. To adjust in the \(x\)-direction pitch should be controlled and in \(y\)-direction it is roll. Of course, the tracking of the object is dependant on it staying in view of the camera. If the quad-rotor looses track of the object and/or it moves out of view the quad-rotor has no information on where the object is located. A way of trying to find the object could be to make the quad-rotor travel in the direction in which the object left the field of view. For example, if the tracked object left the field of view along the \(x\)-axis, the quad-rotor will start to travel in that direction in order to relocate the object.

B. Flying targets

If the target to track is also an airborne craft the tracking becomes more difficult than in the ground object case. An airborne craft can obviously not only move in the \(x, y\)-plane but also in \(z\)-direction. By using a UAV equipped with a front facing camera it can successfully track a target moving in 3D-space. It is difficult, if not impossible, to measure absolute distances from the UAV to objects in its surroundings by only using one camera as sensor input. Relative distances could however be measured by looking at how the size of an object changes between images. A reference size of the object in an image would typically be set at the beginning of the tracking, if the object appears bigger later on in the tracking the UAV is too close to the object and vice versa.

The height and yaw of the UAV could easily be adjusted as to keep the tracked object in the camera view. One interesting aspect when tracking a flying object is that the following UAV does not necessarily follow the same path as the tracked object. Imagine for example that the object to be tracked follows a
circular path centred in a point $a$ in the $x, y$-plane. If the UAV is positioned at $a$ it could just be standing still in the same point while yawing to keep the object in view. It is thus not following the same circular path as the object to be tracked, but it is still monitoring the object at a fixed distance.

XI. AN ORIGINAL APPLICATION WITH QUAD-ROUTERS

Ever since 9/11 the world have feared new terrorist attacks. Governments all over the world have been taking this threat seriously and they have cut no expenses to prevent further attacks. United Nations have the following to say about a persons right to freedom of fear in its Universal Declaration of Human Rights [21]:

“Whereas disregard and contempt for human rights have resulted in barbarous acts which have outraged the conscience of mankind, and the advent of a world in which human beings shall enjoy freedom of speech and belief and freedom from fear and want has been proclaimed as the highest aspiration of the common people.”

One of the most security dense buildings in todays society are airports. Large airports handle vast quantities of passengers every day and a well functioning surveillance system is a necessity for reducing the number of thefts and other threats to the users of the building.

Traditional surveillance of large buildings and locales is performed by using a camera system with fixed camera nodes. To cover an entire airport with fixed cameras is close to impossible since a lot of things change on a day to day basis. Today this problem is often solved by having patrolling human safety personnel. This solution is not complete since it is expensive to employ people, also humans are not suited to perform monotone tasks for long periods of time due to fatigue.

A way to solve this problem is to have small UAVs autonomously patrolling the airport covering all the blind spots of the stationary cameras. Furthermore the UAVs could alert personnel in a control room about suspicious objects and events. Things like unattended luggage would be easy for a computer to find. It is also important to have mobile cameras since terrorist and other criminals tries to avoid being filmed. Also this system could be used to make statistics of how people move and behave in the airport. The same statistics could then be used to find passengers who differs from the regular pattern. Another way in which UAVs could be used in an airport is to follow a suspected person. It would be hard to outrun a flying camera since they are not slowed down by other passengers as a guard would be.

Of course there are always problems with autonomous systems involving UAVs. If used indoors to survey a terminal for an entire day, for example, the UAV must be able to sustain flight for the full period of time or atleast long enough for a replacement UAV to recharge. Also the UAVs must be reliable so the passengers is not at risk of having UAVs crashing in to them. Therefore we believe that lighter than air UAVs are good for routine surveillance. They can sustain flight for longer periods of time and since they require less energy to move around they are generally less noise and thereby causing less disturbance for the public. These lighter than air UAVs could be blimps. They have the advantage of low power consumption and thereby long operating time. However, they have a problem with miniaturization since they are lighter than air they are sensitive to air currents. Their flight speed is also limited so it would not be hard for a suspected person to outrun a blimp.

We think that the best way of implementing this in a real airport would be to have blimps patrolling the airport to cover as many of the blind spots as possible. Faster UAVs such as quad-rotors could be use as emergency vehicle when its high speed and manoeuvrability is needed.

XII. NETWORKED COOPERATION

In the application of using UAVs in a smart building setting it is of interest to arrange for cooperation with other types of robots and sensor networks. Every robot and agent is limited in the kind of tasks it can perform, but by combining a number of smaller systems with each other a larger system with a wide variety of applications can be constructed. As discussed earlier, UAVs have the ability to provide surveillance and monitoring of an area. These capabilities could be combined with a team of AGVs (Autonomous Ground Vehicles) performing tasks on the ground [22]. In order for UAVs and AGVs to understand their current position a WSN (Wireless Sensor Network) consisting of cameras could be used [23]. One would typically have a central server coordinating and giving instructions to each of the subsystems.
Figure 11 shows an idea of how the different systems could be divided and share information. The central server would be keeping track of the overall mission and sending instructions about where each of the agents are to be sent.

The positioning of the agents active in the building are crucial to a mission’s success. The central server uses the positioning capabilities of the WSN but it can also as take into account estimated positions from the different agents. However, since the UAVs’ abilities to position themselves accurately are limited, it is best to rely on the information given by the WSN and perhaps also from the AGVs that in most cases will have a better estimate of it’s position than the UAVs.

The three subsystems could have the functionality as seen in figure 11. The WSN should know what types of objects (tags) to look for in the building, this is managed by the central server. The UAVs and AGVs then receive information on where they are located and transmit other types of data. The UAVs could send back data of their height (given by ultrasound sensor), if they can see any objects (tags) with their cameras and which agents are active or not. The data sent from the AGV system to the server is the estimated positions of the AGVs and if they are active.

To increase the reliability and robustness of the system the sensor data from several sensor nodes could be fused. This would increase the accuracy of the system, as described in a paper by Luo et al [24]. Even though the WSN system most of the time have the best ability to determine position, the AGVs and UAVs can aid with sensor data to give a more exact positioning. For example, the UAVs have fairly reliable height measurements using its on-board ultrasound transceiver, then a weighted mean value of the height could be calculated which should be more reliable than from the individual systems.

Moreover, as the UAVs are equipped with cameras of their own the information obtained with these sensors should be combined with that of the WSN. If, for example, a UAV spots an AGV on the ground right below it, the WSN network should get to know this as it may help in the positioning of the agents.

The subsystem for the UAV part would not only consist of UAVs, a computer would also be involved. This computer would be responsible for forwarding instructions from the central server to the individual UAVs. Setting up the system in this way, it is not necessary for the central server to know exactly how to communicate and send instructions to the UAVs, all it knows is that it can be done. It is thus only needed for the central server to communicate with the UAV computer, the rest is handled by the UAV subsystem.

A nice feature is that it is easy to add or remove agents from the system. This is useful when there is a large building and many agents divided amongst different missions. If there arises an event in the building which should be responded to, agents can be moved from less important missions and added to the new one. Another case could be if a UAV runs out of power and needs to recharge its battery for a while. In the case of removing a UAV from a mission, all that needs to be done is for the UAV computer to notify the central server that

the UAV in question is no longer part of the mission and that the WSN system should no longer try to position it.

Real world applications for such a system as the one presented here are many.

XIII. A PRACTICAL TEST

As a practical test of some selected parts of the theory in this paper a few simple experiments using a commercially developed quad-rotor UAV were conducted. The quad-rotor (See figure 12) comes from the company Parrot and is called AR.DRONE [25]. The UAV is shipped with a well functioning embedded control system to set desired angles (roll, pitch), yaw speed and speed in z-direction. To control the AR.DRONE commands are sent over Wi-Fi that dictates what the desired tilt, yaw speed and lift speed is, the on board control will then adjust the rotor speeds to achieve those values. Hence the only control implemented in the practical test is the part concerning the position of the AR.DRONE in the room. See 13 for a schematic picture of the controller.

The AR.DRONE is equipped with two camera sensors, one facing forwards and one downwards. Specifications of these camera sensors are found in table XIII. The images captured by these cameras are sent as a video stream over Wi-Fi to a receiving device, such as a computer. Other types of sensor data are also distributed, such as accelerometer and gyroscopic readings. Height values from an ultrasound sensor are also sent.

In order to communicate with and control the AR.DRONE a computer program was developed. MATLAB was used to find and track objects in real time from the video stream.

A. Object following using the front camera

The first simulation was of a UAV following an object. This object could for example be another UAV, but for simplicity a red ball was used in the simulation. The AR.DRONE faced
the ball at all times while trying to keep a fixed distance of one meter from the ball to itself. From the image stream of the camera MATLAB was used to calculate the centroid of the red ball. The control algorithm then tried to keep the center of the ball in the center of the camera image. This was done by yawing as a function of the error in $x$ and increasing lift speed as a function of the $y$-error (see figure 14). The controller is the one discussed in section VI-F, however only a PD-controller was used since the integrating part was deemed unnecessary when no steady state errors were encountered.

MATLAB also calculated the area of the ball in the image and then used that to estimate the distance of the ball to the camera. The viewed area $A$ of an object at distance $d$ decreases as the inverse square of $d$. That is $A \propto d^{-2}$, which gives $d = 1/\sqrt{kA}$, where $k$ is a constant. A few simple tests were carried out to verify this, the results can be seen in figure 15. As expected the results in figure 15 coincides with the theory. Some problems occurred when trying to implement this controller. This was because the method of measuring the distance between the ball and quad-rotor was suffering from noise in the images. An illustration of this is given by the line in figure 16. The ball and quad-rotor was placed at a fixed distance from each other and the distance was measured using camera images obtained for around 35 seconds. The standard deviation of the signal was about 4.3 cm at a distance of 1.8 meters. When the quad-rotor was moving the noise was even bigger. Also at some distances the noise was bigger than others and the noise grew as the distance to the ball grew.

By using the control algorithm for the average of the five last measurements and removing spikes that moved more than 20 cm in one sample step the stability of the system was slightly improved.

To conclude the results of this experiment working algorithms was developed and tested. As seen in figure 17 the UAV was able to keep the ball in the centre of its image. Also it was able to stay approximately one meter away from the ball, however, due to the relative high noise (see figure 16) the distance controller did not work as well as the one keeping the ball in the centre of the image.
B. Hovering above an object

To hover and follow an object on the ground has many practical applications. The objective of this experiment was to follow an imagined criminal, both being able to hover and follow the suspect. The same red ball as before have been used for this experiment.

Just hovering above a fixed point carries some difficulties. The first and foremost problem is that the camera facing down on the AR.DRONE is fixed to its body frame. This means that if the AR.DRONE change its pitch or roll the camera would perceive that the ball had moved although nothing yet had happened. We tried to solve this problem by implementing the theory discussed in section X-A. This was not successful, due to shortage of time.

Another problem we faced was that the viewing angle of the camera was only 64°. So if the AR.DRONE was flying at an altitude of 1 meter it could only see a length of maximum 1.25 meters, also note that this length is the diagonal of the picture. From the center of the picture to the closes edge the distance is only about 0.4 meters. So if the AR.DRONE move 40 cm away from the ball it would lose track of it. Therefore the MATLAB program need to always keeping track of where the ball was lost, in order to be able to find its way back even it the ball is not in sight. This problem was partly solved by changing the height at which the UAV flew, allowing the camera to monitor a larger area.

PD-controllers was also implemented for this task. The result was an unstable oscillating motion of the UAV. Although the quad-rotor at times lost sight of the ball it was able to find its way back. But when the UAV found its way back to the target the speed was to great for our controller to act sufficiently. If more time would be given this could probably be solved by tuning the controllers.

In the end we failed to hover stable above an object. The main problem encountered was the body fixed downward facing camera with poor resolution and viewing angle. It is limiting to use sensors with poor detection range.

XIV. DISCUSSION

Unmanned Aerial Vehicles have many different uses, and for each of these uses different properties are needed. It is important when designing a UAV to have this in mind and to choose the appropriate sensors and actuators for the specific use that the UAV will have. However it is also desirable to keep the UAV as low cost and energy efficient as possible. The trade-off between these two factors, cost and accuracy of sensors, is an important concept when designing a UAV.

The importance of accurate sensors became evident when the practical tests of this paper were made. As seen in table XIII, the one of the two cameras that is directed downwards on the AR.DRONE is not close to accurate as the forward facing camera. Because of this there were no problems following a moving object in front of the UAV, while there were huge issues when trying to stay on top of an object on the ground, even a stationary one. However with more time the algorithms and controllers could probably have been improved to successfully track an object on the ground. Nonetheless the difficulty to accomplish this would be substantially lowered if the quality of the camera facing the ground had been as good as the one facing forwards.

Due to a lower price, energy consumption and lower maintenance costs stationary cameras and sensors are in general better suited than mobile UAVs to monitor smart buildings. However, in some cases, when security is amongst the top priorities, larger resources can be spent to keep a building as safe as possible. UAVs can then provide a good compliment to stationary surveillance. Airports, museums, train stations
and shopping malls are some examples of when UAV aided security solutions can be appropriate.

The possibilities to build cheaper, more energy efficient and lighter UAVs will increase the interest of using UAVs in smart surveillance solutions. It is hard to predict how big this increased demand for UAV surveillance will be. One thing is certain though, if the prices to manufacture and purchase small UAVs continue to drop at current rate, the spectrum of uses for UAVs will widen. Just a couple of years ago the only uses for UAVs were military. Today UAVs are used in many different civil applications. They are used to monitor borders, keep track of forest fires [26] or even as toys [25]. Who knows what will happen in the future, maybe swarms of UAVs not bigger than insects [27] will be constantly present in our lives. The uses for such devices seem almost endless. This require that algorithms for swarm intelligence and cooperation keep on improving.

Just imagine having small, cheap and yet completely mobile sensor nodes [28]. That is exactly what the smart homes of the future are going to need. These small insect UAVs could for example be used to measure the temperature in different parts of a room for more efficient heating.

The main idea behind a smart building is that many systems should be connected and cooperate by sharing information between each other. One thing that has become apparent when writing paper is that UAVs benefit greatly from an external system to obtain accurate positioning information. If no such system is available and a UAV uses only its on board sensors (accelerometers, gyroscopes, etcetera) to estimate its position the noise from the sensors will affect the estimation and the positioning will not be accurate. Moreover, as time goes by the error in position increases as the noise from gyroscopes and accelerometers is integrated. It is safe to say that positioning will improve when UAVs are used in combination with a separate sensor network.

The abilities of a wireless sensor network consisting of cameras to position objects in a smart building are discussed in [23]. As this way of positioning objects is dependent on image processing which requires computational power the development of faster processing units will pave the way for better functioning systems.

These are the possibilities for UAVs however there are some problems. The main problem today is energy, especially for UAVs that are heavier than air. Huge progress have been done in the last decade regarding the efficiency of batteries. However, much energy is required to keep for example a quad-rotor airborne. Today, due to no emission of toxic gases, batteries is the best energy source to use in UAVs for indoor usage. The problem with relatively low energy density in batteries is decreasing every day thanks to the progress in manufacturing and development in technology. It is not just batteries that gets lighter and more efficient. Electronic components such as sensors and microchips have also been revolutionized in the last decade. Both the price and weight of such devices have dropped considerably in recent years. While the computational power and reliability have increased.

Another problem that exists today is the problem of personal integrity. People can feel intimidated by being watched and monitored at all times, this is a big issue. The right of personal integrity is a hot topic today. People are afraid that information gathered will come in the hands of the wrong people or that our community will turn into a dystopia like the one described in George Orwell’s novel Nineteen Eighty-Four. At the same time there is always a trade-off. To be able to stop over consumption of energy and the problem of global warming we humans must figure out a way to make our way of living more energy effective. However, surveillance can also be used to make people feel more safe. The balance between what should be accepted and what should not be accepted is important and complicated. Smart buildings can make our way of living more streamlined and therefore helps us to consume less energy and at the same time make our day to day life easier. The fact that today’s UAVs often are noisy and bulky does not help them. We can not imagine that many are interested in investing a lot of money to have a noisy quad-rotor patrolling their house even if would help with surveillance and security in their homes. However, in a not too distant future the price, efficiency, size and noise level of UAVs will hopefully have improved to the point that they are hardly noticeable and become a natural part of our lives.

XV. CONCLUSION

This paper has studied how to use UAVs in a smart building setting. Studies were focused on modelling and control of a quad-rotor UAV. Quad-rotors are versatile because of their ability to move and rotate in narrow spaces while still being able to travel at a relatively fast speed.

One important thing to note is that different UAVs are good at different tasks. While quad-rotors are good at moving at high speeds they might be in a disadvantage for usage in surveillance application in crowded areas. This is due to their high noise and disturbance factor and that they can fall and hit someone if they have an engine failure. Hence, lighter than air vehicles might be better suited for surveillance in smaller spaces where a lot of people are present and quad-rotors are better at missions when speed is of importance and covering distances that are slightly larger.

If the UAVs are to be used without an external position system, extremely good sensors will be needed to determine their locations. Also the sensors must accommodate the needs for the task at hand. Comparing with the experiments done in this report, where some of the tasks was not successfully fulfilled, partly due to poor sensor data. We believe that UAVs in large building complexes have a market potential. Although surveillance using stationary camera nodes using wireless networks is probably more cost efficient in most cases. One thing is certain though, the growth of smart buildings and homes will just increase. Whether UAVs will be a big part of this revolution is yet to be seen. However if the technology keep its current pace we strongly believe that the future for UAVs in smart buildings is very bright.
ACKNOWLEDGEMENTS

We would like to thank our excellent supervisors Farhad Farokhi and Jose Araujo for invaluable support and advise. We would also like to thank Automatic Control Laboratory at the Royal Institute of Technology for a interesting and rewarding project as well as an office to work from.

REFERENCES


