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POSITION CONTROL FOR AUTOMATIC LANDING OF UAV IN A NET ON SHIP

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Abstract

Automatic landing of a fixed wing Unmanned Aerial Vehicle (UAV) in a net on a ship require an accurate positioning system. There exist today high-end systems with such capability for special applications, e.g military systems and costly commercial systems, which restrict the availability of such systems. To increase the general availability these systems must consist of low-cost components. Here, an alternative is the use of low-cost Global Navigation Satellite System (GNSS) receivers and apply Real Time Kinematic GPS (RTK-GPS), which can provide centimeter level position accuracy. However the processing time for the RTK-GPS system results in degraded accuracy when exposed to highly dynamical behaviour.

This work present two alternative software and hardware position systems suitable for use in navigation system which apply RTK-GPS, namely Real-Time Kinematic Library (RTKLIB) with a Ublox Lea M8T receiver and a Piksi system. Both the Piksi and the Ublox receiver are single-frequency GNSS receivers. These systems will in this work be compared and their individual capability to provide accurate position estimate will be evaluated.

The RTK-GPS system is implemented in DUNE (DUNE:Unified Navigation Environment) framework running on an embedded payload computer on-board an Unmanned Aerial Vehicle (UAV).

The performance of these position systems are in this work investigated by experimental testing. The testing showed that the RTKLIB performed better than the Piski alternative, and further showed the tested navigation system provide sufficient quality for integration into a control and guidance system, allowing for automatic landing of an UAV in a net.

Contents

Chapter 1

Introduction

1.1 Background and motivation

Recent development of flying UAVs has been recognized to provide an attractive alternative to work previously performed by manned operations. Typical work which has attracted attention includes inspection, aerial photography, environmental surveillance and search and rescue. Today UAVs are mostly operated over land, however in the future this will include over sea as well. This will give some challenges which must be overcome. One of these challenges is that the UAV need to be able to perform a automatic landing.

An UAV can provide an attractive alternative for many maritime operation where today manned aircraft or satellites is the only solution. In the maritime sector UAV can be used in iceberg management, monitoring of oil spills, search and rescue and maritime traffic monitoring.

An important premise for successful and safe UAV operation, in particular at sea, is the provision of a robust system for safe landing of the UAV on a vessel following completed operations. A autonomous landing system require a robust guidance and navigation system, as well as the ability to generate a the landing path during flight operation. A requirement for the system is that the operator is able to monitor the state of the uav, including the navigation system e.g gps system. The the gps system looses its fixed solution during a critical phase a abort with an evasive manoeuvre might be required. The decision of wheater the uav should perform a evasive manoeuvre will be further explored in section (REF:EVASIVE).

Due to regulatory mandate there are restriction on the size of operational area for a uav. Different types of operation is LOS,EVLOS,BVLOS. During LOS the uav must be in line of sight of the operator, which restrict the area were a autonomous landing can take place. In addition there is the risk of loosing satellites during high dynamic behaviour which limits the type of landing path that are available. Therefore a flyable path must be generated for a arbitrary pose, which will provide a gentle landing for the uav. Present UAV

UAV in a maritime environment

A robust navigation system, which include two position estimation system for relative position determination of the UAV.

The scope of this thesis is the design, implementation and testing of an autonomous landing system for a uav. The main focus in this thesis will be on the navigation and path planning of the landing system. A fellow master student had the main focus of developing the control and guidance system, which will be explain in section ref.

This thesis contain a concept of a robust navigation system for autonomous landing of a UAV, and the implementation of the autonomous landing system. The landing system has been implemented together with a other student, and is a continuation of the master thesis from [**?**]. The navigation system that has been implemented apply rtk-gps for position estimation, and the robust navigation system apply range measurement from local transmitters together with the rtk-gps for position estimation. The range measurement hardware was not ready by the time this master thesis was written, however this thesis will explore different methods that can be applied in order to achieve a robust navigation system.

1.2 Related work

A disadvantage with a net recovery system that is stationary on the deck of a ship is the space requirement for the net, including the safty zone for the personnel required for the uav operation. The paper (Ref multicopter paper when published) addresses this problem by moving the net away from the ship by the means of multirotor uavs. The proposed net recovery system has the advantage that motion induced by the sea is removed, however there is the risk of losing the uav when colliding with the net. A solution that is currently explored is the use of hooks on the uav, which will allow it to grip the net.

Chapter 2

Path planning theory

An autonomous system that is tasked to move from one position to an other require a planed path that is feasible for the system. Therefore a minimum requirement for the plan is that it is connected. The connection level can be described by the paths smoothness. Geometric continuity is a relaxed from of parametric continuity in witch discontinuousness in speed is allowed. Geometric continuity is sufficient for a path following system, witch is the main focus of this thesis. Geometric continuity is denoted as G^n were n is the order of continuity.

Smoothness level in this thesis is follow the the definition given by Anastasios M. Lekkas Lecture 1.

Geometrical smoothness level	**Description**
G^0	All subpaths are connected
G^1	The path-tangential angle is continuous
G^2	The center of curvature is continuous
Parametric smoothness level	**Description**
C^0	All subpaths are connected
C^1	The velocity is continuous
C^2	The acceleration is continuous

Table 2.1: Smoothness definitions

A the definition that is used for path in this thesis is:

$$P_s(x_s, y_s, z_s, \psi_s) \rightarrow P_f(x_f, y_f, z_f, \psi_f) \tag{2.1}$$

were the subscripts s and f denaontes the start pose and finish pose respectfully. This is an relaxed form of the start and finish pose since the pitch and roll angle is assumed stable, and therefore a desired start and finish value is not required.

2.1 Straight lines

The simplest form on path is a straight line between P_s and p_f. The straight line is given as

$$x(t) = a_x t + b_x \tag{2.2a}$$

$$y(t) = a_y t + b_y \tag{2.2b}$$

with $t \in [0, 1]$. Then the parametrisation of the straight line is:

$$x(0) = b_x \rightarrow b_x = x_s \tag{2.3a}$$

$$x(1) = x_f = a_x + b_x \rightarrow a_x = x_f - b_x \tag{2.3b}$$

$$y(0) = b_y \rightarrow b_y = y_s \tag{2.3c}$$

$$y(1) = y_f = a_y + b_y \rightarrow a_y = y_f - b_y \tag{2.3d}$$

$$\tag{2.3e}$$

A path constructed by straight lines is G^0 and C^0, however since the tangential vector is discontinuous between two line segments with different heading it's not G^1 or C^1. The simplest for of creating a path is a straight line between two waypoints. The advantage with a straight line is that it's easy for a guidance system to follow the line, however it will experience a jump in reference when transitioning to another straight line

2.2 Dubins path

An alternative to a straight line path is a path constructed by straight lines and circle. Dubins path [Dubins, 1957]. The path is considered as the shortest path from P_s to P_f, however the curvature is discontinues, which gives a smoothness level of G^1 and C^0. Dubins path is the shortest path from from one waypoint to the other which is continues. Dubins path can be created for a three dimensional case, however a simplification is made in which only a planar version of the Dubins path is examined. A Dubin path with fixed end orientiation can be constructed in four different way.

Right to Right
Right to left
Left to Right
Left to left

Allowing the finish orientation to be free will add four more variants of the Dubins path. The path consist of two arcs and a straight line. The straight line is tangential to both arcs. The start and end point of the straight line can be found with

$$\alpha = \arcsin(\frac{\rho_f - \rho_s}{|c|}) \tag{2.4a}$$

$$\beta = \arctan(\frac{y_{cf} - y_{cs}}{x_{cf} - x_{cs}}) \tag{2.4b}$$

	Turn angle
ϕ_{right}	$\alpha + \beta + \frac{\pi}{2}$
ϕ_{left}	$\beta - \alpha + \frac{3\pi}{2}$

$$x_{P_\chi} = x_{cs} + R_s \cos(\phi) \tag{2.5a}$$

$$y_{P_\chi} = x_{cs} + R_s \sin(\phi) \tag{2.5b}$$

$$x_{P_N} = x_{cf} + R_f \cos(\phi) \tag{2.5c}$$

$$y_{P_N} = x_{cf} + R_f \sin(\phi) \tag{2.5d}$$

Chapter 3

RTKGPS

This chapter present some of the basic theory behind rtkgps.

3.1 Real time kinematic GPS

RTKGPS solution can be obtain by a dual frequency receiver, or two single frequency receivers that are Real Time Kinematic GPS (RTK-GPS) is a variant of Differential GPS (DGPS) where raw data is sent from the base station to the rover, where the distance between them is calculated in real time. The distance between the rover and base station is referred to as a baseline. The difficulty with RTK-GPS is the ability to estimate the integer ambiguities while the rover is moving. A fixed integer ambiguities solution results in a accurate baseline estimate.

RTK-GPS can either provide a kinematic setting or a moving baseline setting. The difference between the two is that in kinematic the base station has a known stationary position, while in moving baseline the base station position is unknown and allowed to move. The unknown base station position is calculated with a single receiver, with the accuracy that entails. Therefore the RTK-GPS system with a moving baseline configuration can never have better global accuracy then what it will get with a single receiver. The advantage with the moving baseline configuration is that RTK-GPS can be used to find the relative position between two dynamical system using GNSS in real time. This will be the case in automatic ship landing system, where the base station is on a ship, thus must be allowed to move. The advantage with kinematic mode is that it can give a more accurate position estimate, where the relative position of the rover can be given in either the North East Down (NED) or East North Up (ENU) frame.

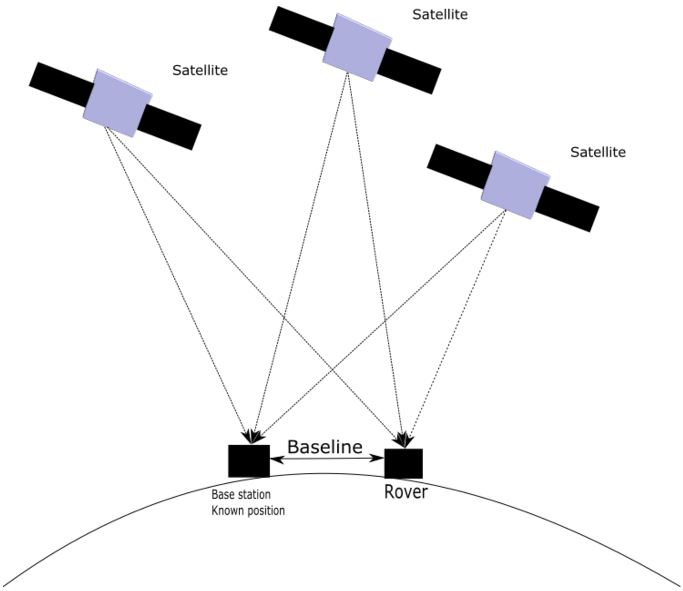

Figure 3.1: Concept figure of Differential GPS (DGPS)

3.2 Error sources

In order to get high accuracy in the position estimation the different error sources must be identified and removed if possible. This section will identify some of the most significant error sources that can affect the Global Positioning System (GPS) signal, and how to remove or mitigate them in the estimation.

3.2.1 Clock error

There is drift in both the satellite clock and the receiver clock. The atomic clock in the satellites makes the clock drift negligible from the user perspective. The receiver clock tend to drift, and if not taken into account will cause large deviations in the position estimate from the true position. This error is remove by including a fourth satellite in the position computation. The satellite clock error is given in the satellite message.

3.2.2 Ionospheric and tropospheric delays

When the GPS signals travel though the atmosphere there will be a delay caused by the different atmospheric layers.

Ionospheric delay

Gas molecules in the ionosphere becomes ionized by the ultraviolet rays that is emitted by the sun, which release free electrons. These electron can influence electromagnetic wave propagation, such as GNSS signals. The delay that the signal get from the ionosphere may cause a error the the order of $1 - 10$meters. The error can be mitigated by using a double frequency receiver, or by applying a mathematical model to estimate the delay. Both those methods are with a single receiver, however by including a second receiver the GNSS solution system can assume that both receiver receive signal in the same epoch, which means that the signals have experienced the same delay. This will be further explain in section 3.3.1.

Tropospheric delay

The tropospheric delay is a function of the local temperature, pressure and relative humidity. The delay can vary from 2.4 meters to 25 meters depending on the elevation angle of the satellites. The error can be mitigated by applying a mathematical model to estimate the tropospheric delay, or by using a elevation mask can remove all satellites with a elevation angle bellow a certain threshold. Error caused by tropospheric delay can be removed in the same manners as ionospheric delay when using two or more receivers. This will be further explain in section 3.3.1.

3.2.3 Ephemeris errors

A satellite is not able to perfectly follow a given orbit, therefore there will be a deviation between satellite position given to the receiver and the true position of the satellite. This is called the ephemeris error. The true position of a satellite is monitored and corrected by the owner of the GNSS constellation, but error between each correction can be expected.

3.2.4 Multipath

One of the primary source of error in in a GNSS receiver is multipath. Multipath happens when the satellite signal is reflected by a nearby surface before if reach the GNSS antenna. The delay introduced in the signal can make the receiver believe that its position is several meters away form its true position. The easiest way to mitigated multipath is to place the antenna at a location with open skies, and no tall structures nearby.

3.3 Differential GPS

Differential GPS (DGPS) consist of at least two receivers, where one is called a base station and the rest rovers. For simplicity only two receiver is used in this section.

The two receivers are within range of a communication channel over which they are communicating, as shown in figure 3.1. The base station has a known position, and the rover estimate the baseline from itself to the base station.

In this project work only carrier phase measurements will be considered for position estimation method. The problem with precise relative positioning with carrier phase measurement is problem of estimation of integer ambiguities.

3.3.1 Error mitigation in DGPS

In DGPS the rover considers that both the rover and base station receive GPS signal that has experienced the same delay. Thus the rover can remove all error sources that is correlated with the base station. This assumption holds given that the baseline is not to long. For longer baseline other methods must be applied to correct for atmospheric delay. DGPS error mitigation do not include multipath. Multipath is an uncorrelated error, and thus must be corrected locally by both the rover and base station.

Chapter 4

System

4.1 Navigation system

The navigation system apply RTKGPS for position and velocity measurement. The RTKGPS solution is calculated by the open source program RtkLib. The output from the RTKGPS software contains only the relative position from the base station, and not the position of the base station. Therefore a task was created to send send the global base station location to the navigation system, which enable the rest of the system to calculate the global position of the uav.

The base station position is received in the RTKGPS task in DUNE, were it's included in the GpsFixRtk message.

A task in the nest receive the gps position of the base, and the operator can monitor it in neptus. When the operator choose to fix the base station gps position a parameter update is send to the task, which will start to send a gpsfixrtk message to the uav.

TODO: Create figure that shows the information flow that is used to create the rtkfix message.

4.1.1 Operator interface

The operator use the Neptus platform as operational interface during the landing. The console includes information about the position of the uav, as well as the source of the position measurement. The operator can monitor the status of the gps system, including what is accepted by the navigation system. During a autonmous landing the operator must be fully aware of the status of the navigation system, such that an abort due to lost gps fix. This system can be expanded to include other sensors, like a ranging system, IMU, camera ex.

4.1.2 Position correction

The highly dynaimcal nature of the uav create a challenge for the navigation system due to the blocking of the gps antenna from the satellite constellation. The problem was reduced by using a gps receiver that has a high performance in satellite tracking, however this does not remove the problem. A float solution from the gps system is valid for some seconds after fix is lost, due to the predictive nature of the Extended Kalman filter in rtklib. However after a seartin amount of time the navigation system swithces over to use the position estimate from the pixhawk, which has a lower accuracy level then the rtk gps system. To increase the accuracy level a offset solution is proposed. By calculating the difference between the fixed rtk gps solution and the position solution from the pixhawk a offset can be found. If the offset can be assumed constant or quasi stationary it can be used to increase to accuracy level for the navigation system enough to allow for completion of critical phases of a manoeuvre. However tests showed that the offset was not constant nor quasi stationary. By applying the offset to the pixhawk position solution the accuracy level will increase, but not enough to allow for execution of critical manoeuvres. In order to make the navigation system more robust, some methods was explored.

4.2 Path generation

The area where the uav can operate is limited by the operator, which restrict the design of a landing path. In addition to the spacial limitation, the operator may choose the rate of descent which the uav should have during landing. The landing path system that has been design allows the operator to specify the length of the landing approach, including the angle of descent. The landing path follows the Dubins path (ref til teori) in the lateral plane, and straight lines in the longitudinal plane. The path is generated from an apitary start positing, and will create a contiues path toward the landing approach where the hight is given by:

$$h1 = \tag{4.1}$$

LIST opp ligningene for WP

The landing path is design with the assumption that the aerial space in which the uav operates is limited. The limitation can be the range of the uav, regulatory limits or weather. In addition the autonomous landing system must be able to perform a safe landing from any initial position. Furthermore the size of the virtual run way should be constructed by the operator. The type of uav operation dictates the maximum size of the landing path. Different types of uav operation is LOS, ELOS, BLOS and BRLOS. Only the first is considered in this thesis, which means that the pilot must have the uav in view during the entire flight. The operator must also be able to control the angle which the uav is descending, which means that the height of the landing path is fixed. Therefore the uav must be at the correct altitude before it can start descending toward the landing net.

A landing algorithm that is proposed consist of glideslopes that forms a staircase, of which the uav can ascend or descend in order to reach the correct heigh to start the landing. The path itself consist of straight lines between waypoints, however the landing path is not generated for a specific controller.

TODO: INSERT ALGORITHM HERE

The controller apply a goto manoeuvre in DUNE, which make a path manager task responsible for following the path. The advantage with this approach is the use of a module that has been thoroughly tested, which limits the source of error is the guidance system. The disadvantage is the path is picewise continues, which will introduce sudden changes in desired state for the controller. A curved path will remove this behaviour, however this will required a controller which is created specially for this path. I addition the autonomous landing achieved in [Skulstad and Syversen, 2014] was performed with a straight line path.

4.2.1 The net approach

The net approach path consist a straight line in the lateral plain, and straight lines in the longitudinal plane. The net approach is defined by four way points which is defined as follows:

$$\mathbf{WP1} = \begin{bmatrix} -a0 \\ 0 \\ h_{nc} + a1\tan(\gamma_a) \end{bmatrix} \tag{4.2a}$$

$$\mathbf{WP2} = \begin{bmatrix} a1 \\ 0 \\ h_{nc} - a1\tan(\gamma_a) \end{bmatrix} \tag{4.2b}$$

$$\mathbf{WP3} = \mathbf{WP2} + \begin{bmatrix} a2 \\ 0 \\ a2\tan(\gamma_d) \end{bmatrix} \tag{4.2c}$$

$$\mathbf{WP4} = \mathbf{WP3} + \begin{bmatrix} a3 \\ 0 \\ 0 \end{bmatrix} \tag{4.2d}$$

were the description of the parameters used is given in table 4.1. The net is placed between the first and second way points such that transitional behaviour do not occur during the finale stage of the net landing. In addition the path has been made with the assumption that the γ_a and γ_d is considered small. This assumption is made to easy the demand of the controllers used in the landing system.

Parameter	**description**
$a0$	The distance behind the net
$a1$	The distance in front of the net
$a2$	The length of the glide slope
$a3$	The length of the approach towards the glide slope
γ_a	The net attack angle
γ_d	The glide slope angle

Table 4.1: Net approach parameters

The way point vectors are rotated into the NED frame by a rotation around the z-axes.

$$WP^n = R(\psi_{net})WP^b \tag{4.3}$$

were ψ_{net} is the heading of the net.

4.2.2 The landing path approach

Given that the length of the landing path, and the angle of descent is given the start pose is defined. That require the uav the to be given a flyable path such that it can start its landing. The landing path system generates an flyable path with a descent angle equal to the glide slope angle for an arbitrary start pose within the uav operational area. The landing path consists of two part, the lateral and the longitudinal. The lateral path is a Dubins path between two way points. This ensure that the path given to to uav will be the shortest continues path from the uav start position. The longitudinal path is a glide slope with a constant angle, expect when the path reach the desired hight which is the heigh of $WP4$.

The landing path approach can be generated in to different way. One mode allow for manual deciding which side the start and finish circle should be in respect on the start pose, and the net landing approach. This allow the operator full control over the landing path, and can choose a landing path that is operation feasible and not necessary the shortest path.

The other mode generate a landing path which is the shortest path from the start pose to the finish pose. That means that the algorithm must consider four different option in regard to the chosen path.

Extra way point

To ensure that the path generation system will generate å flyable path an extra way point is added in the case of the start pose in cause an infeasable dubins path, or an spesial case of Dubins path which has not been implemented. The two case are

4.3 Evasion

To ensure the safety of the operator a evasion controller is used to abort the landing when a successful landing is deemed infeasible or improbable.

4.4 Guidance system

The guidance system consist of two part. Sliding mode controller, and a los controller

4.4.1 Sliding mode controller

For course control the system use a sliding mode controller that was proposed in the paper [Fortuna and Fossen, 2015], which USGES stability property.

$$\dot{x} = V_a \cos(\psi) + W_x = V_g \cos(\psi) \tag{4.5a}$$

$$\dot{y} = V_a \sin(\psi) + W_y = V_g \sin(\psi) \tag{4.5b}$$

$$\dot{phi} = \frac{g}{V_a} \tan(\varphi) \tag{4.5c}$$

$$\dot{\varphi} = -\frac{\varphi - \varphi_{cmd}}{T_\varphi} \tag{4.5d}$$

$$W = \sqrt{W_x^2 + W_y^2} \tag{4.5e}$$

$$\epsilon(\varphi) = \begin{cases} \cos(\varphi), & \text{if } |\cos(\varphi)| \geq \epsilon' \\ \epsilon', & \text{if } 0 \leq \cos(\varphi) < \epsilon' \\ -\epsilon', & \text{if} - \epsilon' < \cos(\varphi) < 0 \end{cases} \tag{4.6}$$

$$\chi = \tan^{-1}(\frac{\dot{y}}{\dot{x}}) \tag{4.7}$$

$$\dot{\chi} = \frac{g \sin(\varphi)(V_a + \cos(\psi)W_x + \sin(\psi)W_y}{\epsilon(\varphi)V_g^2} \tag{4.8}$$

$$\chi_d = \tan^{-1}(-\frac{t}{\Delta} \tag{4.9a}$$

$$\dot{\chi_d} = -\frac{\Delta}{\Delta^2 + y^2}\dot{y} \tag{4.9b}$$

$$\ddot{\chi} = \frac{\Delta}{(\Delta^2 + y^2)^2}(2y\dot{y}^2 - (\Delta^2 + y^2)\ddot{y}) \tag{4.9c}$$

$$\tilde{\chi} = \chi - \chi_d \tag{4.10}$$

$$s = \dot{\tilde{\chi}} + \lambda\tilde{\chi} \tag{4.11}$$

$$u = -\lambda\dot{\tilde{\chi}} - \rho \mathrm{sgn}(s) - K_d s \tag{4.12}$$

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