Regulative Control in Unmanned Aerial Vehicles
Abstract

Regulative control is an extension of reactive control. It regulates the behavioral responses of the reactive structure, based on the current situation the agent is in. This focus of this thesis is on the application of regulative control to the field of Unmanned Aerial Vehicles (UAVs). One of the problems with implementing regulative control in UAVs is that a typical control system for UAVs is not reactive in nature. Therefore only the idea of regulative control (i.e. regulating the control flow) is used as source of inspiration in implementing a regulative component. Two regulative modules with functional relevance in the field of UAVs are implemented: a wind module and a location module. The wind module monitors the wind conditions the UAV is in and adjusts the route of the UAV when it is found the UAV is not able to follow its route anymore (i.e. it will be blown off track). The location module keeps track of the environment and detects dangerous zones (e.g. when there is a fire, the smoke creates a dangerous zone). When a dangerous zone is found the module leads the UAV around it.

By analyzing the control structure of the UAV used in this thesis, an analysis is made of how the regulative component should be implemented. The two modules are used to test the regulative component and check how well it works in practice. Results show that both modules work as expected. With respect to regulative control, the regulative component preserves the idea of regulative control. There are also some significant differences. One of the main differences is that the regulative component can only trigger functionality as opposed to also block functionality. Another difference is that the modules in the regulative component need to be clearly specified. The black box approach is not suitable, since the operator needs to know what is happening during flight.
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Chapter 1

Introduction

The advances in powerful micro-processors, battery capacity and the availability of cheap and lightweight airframes has sparked new interest in (small) Unmanned Aerial Vehicles (UAVs). Not only are the UAVs useful for military purposes (e.g. surveillance, reconnaissance, weapons platform), civilian applications are now also within reach. Examples of such civilian applications are observation (e.g. traffic observation), remote sensing, search and rescue and mapping. The small size and low weight enables the UAVs to explore new places that full sized aircrafts would not be able to explore. The low costs make the UAVs expandable and ideal candidates for executing possibly dangerous missions.

1.1 UAV Basics

In the field of UAVs a user or operator refers to the person that controls the UAV, where control can range from direct control (i.e. a radio controller) to control through a Ground Control Station (GCS). The GCS allows an operator to monitor the UAV and send commands to the UAV (see also Section 2.1.2). The GSC can be used to specify the mission at a more abstract level than just to send direct commands to the UAV. The mission defines the tasks the UAV needs to perform. An example of a mission would be: observe area $X$ and drop a sensor at location $Y$. The UAV can be a rotorcraft or a fixed-wing aircraft or any other type of aircraft (e.g. flapping wing UAVs are becoming increasingly popular). In this thesis it is assumed the UAV is a fixed-wing aircraft, but the results are generalizable to other types of aircrafts as well. Most UAVs can also transport goods, which is referred to as payload. Given that most UAVs are lightweight, the weight of the payload is also limited. Common payloads in smaller UAVs are sensors (e.g. a camera).

A quick introduction to the flight dynamics of an aircraft is useful for a better understanding of the rest of this thesis. To change direction in air an aircraft can move around three axes of rotation, referred to as pitch ($\theta$), roll
(φ) and yaw (ψ). Pitch is the movement along the lateral axis (moving the nose of the aircraft up and down), roll is movement around the longitudinal axis (rolling the nose of the aircraft in a clockwise or anticlockwise fashion) and yaw is movement around the vertical axis (moving the nose left and right). An aircraft with its three axis of rotation is displayed in Figure 1.1.

1.2 Challenges in UAVs

Unmanned Aerial Vehicles is an active field of research. The UAVs nowadays are capable of autonomous take-off, waypoint navigation and landing (Roos & Peddle, 2009; Chao, Cao, & Chen, 2010). Research focuses on a number of areas. Situational awareness (Suresh & Ghose, 2010), multi-agent cooperation (Bethke, Valenti, & How, 2007), sensor fusion (Merino, Caballero, Martinez-de Dios, & Ollero, 2005) and biologically inspired approaches (Gerke et al., 2011) are a few examples of these research areas. The hardware and aerodynamics of UAVs is also an area of research (de Croon, de Clerq, Ruijsink, Remes, & de Wagter, 2009).

One of the challenges in UAV research is the limited payload the UAVs can carry. Most smaller UAVs (or MAVs: micro air vehicles) are only equipped with a camera. All relevant information for the UAV should then be extracted from this camera feed (de Wagter & Mulder, 2005). Another challenge is the limited battery capacity of (the smaller) UAVs. The operator should take the capacity of the UAV into account when planning a mission, or rely on service stations for recharging (Kemper, Suzuki, & Morrison, 2011). Other challenges include reducing the workload of the operator (Amelink, 2010) and the safety of the UAV.

\[^1\]Picture adopted from [http://quest.arc.nasa.gov/aero/virtual/demo/aeronautics/tutorial/motion.html](http://quest.arc.nasa.gov/aero/virtual/demo/aeronautics/tutorial/motion.html)
1.3 Research Aims

In robotic control inputs are mapped to outputs by means of a controller. Regulative control tries to regulate the input $\rightarrow$ output mapping of the controller based on the state of both the agent and the environment. The idea of regulative control is displayed in Figure 1.2. Regulation can range from inhibition (e.g. blocking an input $\rightarrow$ output mapping) to excitation (e.g. overriding outputs) to adjusting parameters (e.g. changing thresholds). The regulative component should not be confused with a planning component. In contrast to a planning component the regulative component does not make decisions and does not actively model the world. The regulative component merely influences the normal control flow of the agent.

Regulative control is an extension of reactive control in robotics. In reactive control a short, direct route between input and output is created. Common examples of reactive behaviors are sensing food (input) and starting to eat (output), detecting an enemy (input) and flee (output). In the context of UAVs an of reactive behavior could be detecting that the aircraft is about to fly into a cloud (input) and avoiding it (output). Regulative control tries to regulate these input $\rightarrow$ output mappings based on information about the current situation (i.e. based on the state of the aircraft and the environment the aircraft is in). Inhibition is one of the obvious examples in regulative control. In the case of detecting cloud $\rightarrow$ avoidance, regulative control could inhibit the avoidance output when it ‘knows’ the cloud is too large for the UAV to fly around. A more detailed explanation of regulative control is given in Section 2.2. In Section 4.3.2 the criticisms on regulative control are discussed.

The application of regulative control to the field of UAVs is interesting for a number of reasons. The first reason is that implementing regulative control in the field of UAVs is an explorative study. An already existing UAV platform is given and regulative control is applied to this platform. The implementation may lead to new ideas about regulative control in general and show some of the shortcomings of regulative control in general and in the application to the field.
of UAVs. The second reason is that the complexity of both the environment and the aircraft serve as an interesting test-case for regulative control. Regulative control has already been tested in a small environment with an agent having a limited set of sensors and actuators (Lagarde, Kuyper-Sprinkhuizen, de Croon, & Haselager, 2010). The dynamic environment and the complex mechanics of the aircraft pose a challenge for regulative control. The number of input → output mappings in the control structure of the UAV is expected to be relatively large. All these mappings may be influenced by regulative control. This also leads to the second reason for the interest in the application of regulative control to the field of UAVs. The design and implementation of UAV control can benefit from regulative control. The idea of regulative control is that by regulating the control of an agent, more advanced behavior can be achieved. The relatively large number of input → output mappings in UAV control may benefit from the regulation.

The idea of regulative control is applied to the field of UAVs, specifically the area of UAV control. It is important to note that regulative control cannot be (directly) transferred to the field of UAVs. The UAV platform is given and not specifically developed to work with regulative control as was the case in (Lagarde et al., 2010). The challenges in applying regulative control to the field of UAVs are explained further in Section 2.2.1. Regulative control serves as the inspiration for the implementation of a regulative component in this thesis. A regulative component is introduced that regulates parameters and functionality in the control structure of the UAV. It is hypothesized that the design of control algorithms in UAVs can benefit from the ideas of regulative control in two ways. First, by introducing a new regulative component it should become more intuitive to implement new control algorithms. Second, using this new regulative component leaves the ‘reactive’ part intact when implementing new control algorithms.

1.3.1 Research Questions

The research questions that are discussed in this thesis are listed below.

1. How does regulative control fit into the field of UAVs?

As noted in Section 1.3 regulative control is not directly applicable to the field of UAVs. The reactive part on which regulative control operates is missing. Regulative control therefore only serves as the inspiration for the regulative component that is implemented in this thesis. The fit of regulative control into the field of UAVs is measured by identifying the usable parts and ideas of regulative control in general that can be applied to regulative control in UAVs. An analysis of the current control structure in UAVs and an implementation of the ideas of regulative control help in the identification of the usable parts and ideas of regulative control.

\[\text{Here the word ‘reactive’ is used to refer to the levels of control sophistication in the domain of UAVs (see also Section 2.2.1).}\]
2. Is regulative control feasible in the complex dynamics of UAVs?

The control of the UAV (Section 1.1) combined with the complex environment which the UAV is situated in, makes the task of control interesting. The feasibility of regulative control in UAVs is measured by implementing two modules that regulate control of the UAV: a wind module and a location module. The modules lead to more advanced behaviors of the UAV, since the UAV can now cope with more situations (i.e. strong winds and dangerous locations). The implementation provides information about the requirements of the modules to regulate control. Regulative control is considered not feasible when the requirements cannot be met by the current control structure of UAVs. For regulative control to be considered feasible in the field of UAVs the two modules should also work in simulation.

The idea of regulative control is implemented by extending the control hierarchy that is used in UAVs (Amelink, 2010). The new component provides an overview of all the levels in the hierarchy (see Figure 2.9b). To answer the first research question, the different levels of the hierarchy are analyzed and a list is made of all parameters and functionality found in these levels. Relevant parameters and functionality on which the regulative component should operate are then identified. The research question also asks for a discussion of the difference between the implemented regulative component and regulative control in general.

With respect to the second research question, two modules are implemented that have a functional purpose in UAV control. The first module is a wind module that takes the current weather conditions of the UAV into consideration and makes adjustments to the route when necessary (i.e. wind is too strong for the UAV to follow the given route). The second module is a location module that checks for areas where the UAV should not fly in and re-routes the UAV around such areas. The implementation of the two modules helps in determining the types of connections the regulative component should have to the control hierarchy. Simulations with both modules are used to evaluate the feasibility of regulative control. The modules should at least work properly for regulative control to be considered feasible.

1.4 Related Research

This thesis builds on the idea of regulative control (Haselager, van Dijk, & van Rooij, 2008; van Dijk, Kerhofs, van Rooij, & Haselager, 2008). These papers present the idea of regulative control. A previous study by Lagarde et al. (2010) showed regulative control implemented as a neural network regulating a subsumption architecture. This study demonstrated the feasibility of regulative control in a small 2D-world. A complexity analysis by Wareham, Kwisthout, Haselager, and van Rooij (2011) showed that adapting reactive structures is computationally feasible given that the sensory and perceptual complexity is limited (i.e. fixed-parameter tractable). The complexity analysis performed
by Vroon (2011) concluded that regulative control requires at most as many resources as a hierarchical system. Other studies implemented control structures similar to regulative control (Grossmann & Poli, 1998; Scheutz, 2004), with the difference that the design choices are based on an engineering approach rather than a biologically inspired approach.

In the area of UAVs the work of Chao et al. (2010) gives an overview of the different autopilot control systems that are available. An overview of different control architectures for UAVs is given in Narayan, Wu, Campbell, and Walker (2007). An extensive analysis of the levels of autonomy in UAVs is made by Suresh and Ghose (2010).

1.5 Structure

The rest of this thesis is structured as follows. First, Chapter 2 starts by describing the software, the Aoife project, that is used for this thesis (Section 2.1). Then an overview of regulative control is given (Section 2.2) and the relation of regulative control to the Aoife project (Section 2.2.1). The modules that will be used to test regulative control are then described in detail (Sections 2.3-2.4). Chapter 3 continues by given an analysis of the control sophistication hierarchy (Section 3.1). Then the results for the two modules are given separately (Sections 3.2-3.3). The results are discussed in Chapter 4. The chapter starts by discussing the results of the wind and location module (Section 4.1 and 4.2). Regulative control is discussed next (Section 4.3), followed by the research questions (Section 4.4). The chapter concludes by giving ideas about future research (Section 4.5).
Chapter 2

Method

Testing UAVs in the real world is rather expensive, both in hardware and time. The simulation environment Aoife is therefore used to implement and test the ideas of this thesis in. This chapter will introduce the Aoife project (Section 2.1) and the ideas of Regulative Control and their applications to the field of UAVs (Section 2.2).

2.1 Aoife Project

The Aoife\textsuperscript{1} project is a D-CIS/Thales project that implements an autopilot for a UAV, a digital simulator to run the UAV in and a ground control station to control the UAV with. The project builds on the insights gained from the work domain analysis of UAVs by Amelink (2010). The three components of the Aoife project will be explained in more detail in the sections 2.1.1-2.1.3. All three components work together: the simulator executes the commands from the autopilot (e.g. set roll to a specific amount), the autopilot receives inputs from both simulator and GCS (e.g. respectively, the current position and the current route), and the GCS receives inputs from both autopilot and simulator (e.g. respectively, current settings of the autopilot and the current GPS location of the UAV). This interaction of components is displayed in Figure 2.1. The figure also shows that the user interacts through the GCS.

2.1.1 Flightgear

The Flightgear software package\textsuperscript{2} is an open-source, realistic flight simulator. It simulates the physics and dynamics of airplanes in flight. The Flightgear simulator is actively developed and contains many useful features, one of which is configurable weather models. The simulator is specifically designed for research purposes; it provides easy access to the data of the UAV. A connection can be

\textsuperscript{1}See http://en.wikipedia.org/wiki/Children_of_Lir for the origin of the name Aoife

\textsuperscript{2}http://www.flightgear.org/
Figure 2.1: The three components of the Aoife project and the user. The user interacts through the GCS. The GCS receives inputs from the simulator and autopilot. The simulator receives inputs from the simulator and the GCS. The Simulator receives inputs from the autopilot.

made with Flightgear from which real-time data of the UAV can be read (e.g. groundspeed and heading) and on which commands to the UAV can be given (e.g. bank angle and amount of thrust). The simulator displays the UAV in flight in a world as can be seen in Figure 2.2. Different camera views can be used. One notable camera view is the one as displayed in Figure 2.2. The view is from the onboard camera where the camera points to a user defined location. The onboard camera view will be explained in more detail in Section 2.1.2.

2.1.2 Ground Control Station

The Ground Control Station (GCS) lets a user control the UAV. The GCS serves as an interface between the user and the UAV. One view of the GCS provides the user with a map on which the user can create a mission for the UAV to execute. Ideally the user would give a high-level specification of what the UAV should do (e.g. observe this area and report any unusual activity), but this level of autonomy in the GCS is currently not available. Although the GCS is still under development, the available functionality of the GCS suffices to answer the research questions in this thesis.

A screenshot of the GCS with a map view can be found in Figure 2.3. Here a part of the map of the Netherlands is displayed with the black rectangle-like shape representing the route the UAV has to fly. The cross represents the center of the screen. The idea of the UAV is to have a camera on board that can be pointed to a (realtime) user-defined location. The eye in the center of the area enclosed by the route represents this location. This eye can be moved around freely across the map by the operator. The Flightgear simulator will point the camera to this location marked by the eye and keep the camera locked to that location (see also Figure 2.2). Although the camera is now only used and controlled by the operator, the video feed might provide interesting data about the situation the UAV is in (de Wagter & Mulder, 2005).
Figure 2.2: A typical view in Flightgear. The onboard camera view is displayed. The camera is pointed at a location as defined by the user in the GCS. When the UAV makes a turn to the left, the camera will turn to the right as to keep the location it is pointed at in sight.

Figure 2.3: The GSC with a map view, displaying a (closed) route that the UAV will try to follow. The star-like shapes at the corners of the route are the waypoints (see section 2.1.2) that define the actual route. The cross defines the center of the displayed map. The eye just above the cross is the look-at point at which the onboard camera is focussed.
Waypoints

Since high-level specification of the mission is not yet available in the GCS, the user now has to indicate by means of waypoints the route the UAV has to follow. An example of a route is given in Figure 2.3. Note that the route is always a closed loop in the current implementation. The star-like objects on the outer sides of the four corners of the route are the waypoints. The user can drag these waypoints freely across the map. When the position of a waypoint is changed, the route is recalculated and updated.

There are two types of waypoints: fly-over waypoints and fly-by waypoints. The first type of waypoints (i.e., fly-over) are used to indicate waypoints that need to be crossed vertically by the UAV. The fly-by waypoints mark transitions between two paths and need not to be crossed vertically. The current implementation of the GCS only implements fly-by waypoints.

Route Construction

Based on the location of the waypoints, a closed route must be constructed. The challenge is that there need to be smooth transitions between different waypoints so that the UAV will be able to follow the route in air (e.g., no 90 degrees turns). These smooth transitions are created by using the circumference of circles to guide the UAV from one path to another (see Figure 2.4). The smaller the diameter of the circle, the sharper the angles between two paths can be. However, an angle can also be too sharp for a given circle to create a fluent transition. In these cases the circle is placed over the waypoint with two additional circles guiding the route to the entrance and exit of the main circle, as can be seen in Figure 2.5b. The circles used in route construction are referred to as transition circles.

Parameters

The GCS also lets the user set various parameters, related to both UAV (e.g., PID settings, see also Section 2.1.3) and GCS (e.g., the radius of the circles). The parameters are stored in a property tree that is shared between the GCS and the Autopilot. Waypoints are also stored in this property tree. The property tree makes it easy to share parameters between different parts of the Aoife project, while maintaining modularity; the different parts of the projects (i.e., GCS and Autopilot) do not need to communicate directly.

The current implementation of the GCS provides a view of the property tree where the user can change parameters. An example of this view can be found in Figure 2.6. Future versions of the GCS should implement the parameter viewing and editing in a more intuitive fashion.

2.1.3 Autopilot

The autopilot controls the UAV and executes the planning from GSC (Chao et al., 2010). Based on inputs and parameters, the autopilot calculates the
Figure 2.4: Route construction using circles to create smooth connections between different paths.

(a) A route where the angle between two paths is too sharp to create a ‘normal’ transition. Instead, a route is created around the waypoint.

(b) Route construction using circles on a route where the angle between two paths is too sharp to create a smooth transition with only one circle. Extra circles are used to guide the UAV onto and off the main circle around the waypoint. Here only one such extra circle is displayed.

Figure 2.5: Routes with sharp angles between waypoints.
Figure 2.6: The GCS with a parameter view. Internally the parameters are stored in a tree. The current implementation of the GCS displays all the leaves in the tree as separate items on the parameter list.

commands that need to be sent to the UAV to successfully follow the route as given by the GCS (see Section 2.1.2). The connection between the autopilot and Flightgear supports the following commands to be sent:

- **Pitch, Roll, Throttle.** These are the primary commands that are used to steer the UAV and control its speed and altitude.

- **Rudder.** While this command can be used to control the yaw of the UAV, it is currently not used by the autopilot (i.e. the rudder command is set to 0).

- **Brakes.** The left and right break of the gear of the UAV can be set with these commands. The Aoife project currently assumes the UAV to be flying and not to have any ground contact; these commands are not used (i.e. brake commands are set to 0).

- **Camera target (latitude, longitude, altitude).** The camera of the UAV (see Section 2.1.1) will be pointed to the location as specified by this command.

The autopilot also needs feedback from the UAV. The values that flow back from Flightgear to the autopilot are as follows:

- **Location.** The current location of the UAV as a tuple consisting of the longitude (degrees), latitude (degrees) and altitude (feet) of the UAV.

- **Velocities (1).** The groundspeed and airspeed of the UAV measured in knots.

- **Velocities (2).** The velocities of the UAV in the North, East and Down coordinate system, measured in feet per second.

- **Pitch, Roll, Heading.** The current orientation values of the UAV.

- **Rate $\phi$, Rate $\theta$, Rate $\psi$.** Respectively the roll rate, pitch rate and yaw rate measured in radians per second.
Route Following

One of the tasks of the Autopilot is to follow the route as specified by the GCS. To do this, the route is divided into segments. A segment is either a line or (part of) a circle. The route as displayed in Figure 2.3 would contain eight segments: four segments for the corners and four segments for the straight lines between the corners. A segment is said to be active when the UAV is following the route of that particular segment. The Autopilot continuously compares the current location of the UAV to the currently active segment. A distance is calculated between the current position of UAV and the closest point on the active segment, called the cross-track error. The autopilot will try to minimize this cross-track error by adjusting the roll of the UAV.

PID Controllers

The Autopilot makes extensive use of so-called PID controllers. The abbreviation PID stands for Proportional-Integral-Derivative controller and is a widely used control loop feedback mechanism in control systems. A PID-controller tries to minimize the difference (error) between a measured output and the desired output. Based on this error the controller calculates how values should be set to get to the desired output. An example of a PID-controller in the autopilot of the Aoife project is the PID-controller on the altitude of the UAV. Based on the current altitude and the desired altitude the amount of throttle is adjusted.

A PID-controller consists of three terms: the proportional, integral and derivative terms. The proportional term is a term that is proportional to the current error. The integral term is proportional to the integral of the error, which means it takes into account the magnitude of the error as well as the duration of the error. The derivative term is proportional to the derivative of the error and thus tries to predict the future error by taking into account the rate of change of the error. The combination of the three terms is captured by Formula 2.1.

\[ u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{d}{dt} e(t) \]  

where:

- \( K_p \): Proportional gain
- \( K_i \): Integral gain
- \( K_d \): Derivative gain
- \( e \): Error, the difference between the desired output and the actual output.
- \( t \): Time

The \( K \)-terms are the parameters of the PID controller. These parameters can be set by the user in the GCS and will then be used by the Autopilot (see Section 2.1.2). The autopilot tries to minimize the cross-track error by using a PID-controller. By adjusting the bank angle to correct for deviations from the route, the UAV will overshoot the route and start to oscillate. These oscillations
are most notable at the start of the flight when the UAV just found a way onto the route, as can be seen in Figure 2.7. Later in flight these oscillations are much less pronounced as they decrease in amplitude and frequency.

2.2 Regulative Control

The reactive paradigm is a well-known paradigm for behavioral control in robotics. It is based on the idea that behavioral control should not rely on high level reasoning (e.g. planning), but instead rely on direct interactions of the robot with its environment. The dominant approach in reactive robotics is the subsumption architecture (Brooks, 1986). The subsumption architecture defines a (vertical) layered system of behaviors where higher level behavior can override the behaviors of lower level behaviors. An example of such a subsumption architecture is given in Figure 2.8a. The sensory data is fed to the layers. Each layer is then a separate process that determines how to react based on this input. The output is sent to the actuators, where outputs from higher level layers override outputs from lower level layers.

Regulative control (Haselager et al., 2008; van Dijk et al., 2008) in robotics extends the reactive paradigm by introducing a mechanism that can have a regulative influence on the reactive system. In reactive robotics there typically is a fast sense → act connection: the robot reacts directly to inputs from its environment. The regulative mechanism tries to influence these sense → act connections where necessary. One obvious influence of the regulative component would be to block a connection. Although a given input (e.g. seeing food) triggers an action (e.g. eat food), the regulative component might decide (e.g.
(a) Graphical representation of the subsumption architecture. Higher level layers override outputs from lower level layers.

(b) Graphical representation of the regulative control architecture. The regulative component can influence the outputs from each layer in the hierarchical system.

Figure 2.8: Graphical representations of the subsumption architecture and the regulative control architecture. The subsumption architecture is extended by the regulative control architecture by introducing a regulative component (represented by the circle).

Based on contextual information) that this connection is now inhibited: the robot will not eat. A graphical representation of regulative control on the subsumption architecture is displayed in Figure 2.8b. The regulative component can (but not need to) influence each output from every layer in the hierarchical system.

The following example is based on research by Lagarde et al. (2010) and demonstrates the usefulness of a regulative component. An agent lives in a 2 dimensional world filled with food and obstacles, where food is essential to increase the energy of the agent and thus keep the agent alive, and obstacles need to be avoided as they decrease the energy of the agent. This environment also has a day and night rhythm. At day the agent sees everything perfectly clear, but at night it is hard to see and the agent might mistake food for obstacles and vice versa. By using a inhibitory regulative component (i.e. a regulative component that only inhibits outputs from the reactive system) the agent can be put to sleep at night by inhibiting all necessary layers. By doing so the agent avoids walking into obstacles. Although the same sleeping behavior could have been achieved by adding a layer to the hierarchical system that cancels the outputs of all other layers, this would require a structural change in the hierarchical system likely leading to more complex networks, whereas this is not the case with a regulative component (Vroon, 2011). Also, the regulative component is an active learning component: it can learn from experience which layers to inhibit under what circumstances.

The ideas of regulative control served as inspiration for extending the control structures in UAVs. The following sections focus on the implementation of a regulative component.
2.2.1 Regulative Control in Aoife

In the work of Amelink (2010) a work domain analysis is performed on the SmartUAV platform\(^3\). In this analysis six levels of control sophistication are identified: flight, flight control, aviate, navigate, mission and joint mission. These levels form a hierarchy where higher levels depend on the functioning of lower levels as is depicted in Figure 2.9a. Each level is concerned with a specific control problem. The joint mission level is used for joint control of multiple UAVs. The current implementation of Aoife does not yet support joint control of multiple UAVs. The control problem of the mission level is mission control for single UAVs. At this level the mission objectives are described. Examples of mission objects are take-off, observation, object identification and landing. The navigate level is concerned with the navigation of the UAV. Based on information like GPS location, speed and course, it tries to get the UAV from point A to point B. The aviate level is focussed on safely flying the UAV by planning a path and avoiding obstacles. The flight control level is the fifth level and deals with (automatic) controlled flight. It deals with the dynamics of flying a UAV. The sixth and last level is the flight level and is concerned with the flying platform itself. At this level the parameters of the UAV are specified. Examples are the type of aircraft (e.g. fixed wing, helicopter, quadcopter) and endurance (battery capacity).

The control sophistication hierarchy in Figure 2.9a shows a hierarchy with information flowing from top to bottom (i.e. higher levels influence lower levels). It would be interesting to extend this control sophistication hierarchy by introducing a regulative component, inspired by regulative control. Regulative control itself is not (directly) applicable to the control sophistication hierarchy, since the hierarchy is a work domain analysis and not a control structure in itself. Therefore, inspired by the ideas of regulative control, an effort is made in extending the control sophistication hierarchy with a regulative component. The addition of a regulative component provides an overview of all levels in the hierarchy. It allows the regulative component to keep track of parameters at different levels in the hierarchy without interfering with the hierarchical structure of the six levels of control sophistication. In addition to keeping track of parameters, the regulative component can also change parameters and trigger specific functionality (e.g. path planning) on the different levels in the hierarchy. One advantage of this regulative control approach is that by identifying new control problems that do not fit into one specific level of control sophistication, the control sophistication hierarchy can be left intact by placing the new control problem in the regulative control component. Another advantage is that the regulative component allows for regulative control of the UAV; based on current information from the environment and internal sensors the functioning of the UAV can be regulated. A graphical representation of the addition of a regulative component to the control sophistication hierarchy is displayed

\(^3\)SmartUAV is, like Aoife, a software package for UAV control. It is used as a demonstration platform for new technology and as a research platform. SmartUAV is a collaborative project of the D-CIS Lab and ASTI (Aerospace Software and Technologies Institute).
Figure 2.9: Graphical representations of the six levels of control sophistication (2.9a) where higher levels depend on the functioning of lower levels. Figure 2.9b displays regulative control applied to the six levels of control sophistication. The regulative component is able to get information from and influence the levels in the hierarchy.
in Figure 2.9b. As can be seen in this figure the regulative component serves as a container for modules that benefit from the ‘overview structure’ of the hierarchy. A characteristic of modules that would be placed in the regulative component is that these modules do not fit into one specific level of the control sophistication hierarchy. They either do not belong to an existing level at all or need to be placed at multiple levels in the hierarchy. Two examples of such regulative modules are already given in Figure 2.9b: weather conditions and interesting locations. These control problems need access to different levels in the control sophistication hierarchy in order to work properly (as will be further explained in Sections 2.3-2.4). Instead of scattering the functionality of these modules across multiple levels in the control sophistication hierarchy, the regulative component serves as a container for the modules.

**Implementation**

The regulative component is a container for modules. It provides access to the parameters and functionality of the UAV that are found in the control sophistication hierarchy. This concept is displayed in Figure 2.9b. An overview of the parameters and functionality found in the Aoife project together with the associated levels in the hierarchy can be found in Figure 3.1. The regulative component can access all of these parameters and all the functionality. By changing a parameter in the hierarchy all levels in the hierarchy will use this new parameter value, directly or indirectly, and the overall behavior of the hierarchical system is changed. Modules are added to the regulative component and can therefore also use the connections to the parameters and functionality of the UAV. A module has access to all parameters and functionality in the hierarchy and the module should know which parameters and functionality is relevant.

An example of a module in the regulative component is the wind module. The wind module continuously monitors the weather conditions, or more specifically, the wind conditions. The wind module calculates the minimum turn radius of the UAV based on these wind conditions and the maximum bank angle of the UAV (see Section 2.3 for a more in-depth explanation). Note that the maximum bank angle is a parameter found in the hierarchy. The result of the calculations is compared to the radius of the transition circles, which is also a parameter found in the hierarchy.

When the UAV is not able to fly its route (i.e. the minimum turn radius is greater than the radius of the transition circles), the module updates the radius of the transitions circles to a value with which the UAV would be able to fly its route again. The module then triggers a route re-plan, which is a functionality found in the hierarchy. It should be noted that the different parameters that are used by the module are found in different levels in the hierarchy.

In the implementation of the regulative component in the Aoife project modules are added to a list. The modules in this list are continuously executed in the order they appear on the list. Each module can use and adjust parameters and execute functionality in the hierarchy. In the current implementation there is no communication between modules; one module cannot rely on the execution
and results of another module.

2.3 Wind Module

Making a turn in air requires the aircraft to roll to a banked position in such a way that the wings are angled towards the desired direction of the turn. In level flight the forces on the aircraft are in balance; the lift force is equal to the gravitational force on the aircraft. In a banked turn these forces change. Figure 2.10 shows the forces acting on an aircraft executing a banked turn. The horizontal component in this figure represents the centripetal force and is responsible for executing the turn. Having the aircraft execute a banked turn for some time will eventually result in the aircraft flying a full circle. The radius of this circle is referred to as the turn radius. The turn radius becomes larger when the bank angle decreases (smaller $\theta$ $\rightarrow$ smaller centripetal force $\rightarrow$ larger turn radius) and smaller when the bank angle increases (larger $\theta$ $\rightarrow$ larger centripetal force $\rightarrow$ smaller turn radius), all other factors left equal.

The bank angle of an aircraft is limited to a maximum. Exceeding the maximum bank angle could put the aircraft in danger: it might put a lot of stress on the aircraft or it might have the aircraft flip over when dealing with lightweight aircrafts. Given that the turn radius and bank angle are dependent, this constraint on the bank angle also poses a constraint on the minimum turn radius (although it is important to note that the turn radius also depends on other variables than just the bank angle). This is interesting when considering that the route planning algorithm uses transition circles to connect paths between waypoints (see Section 2.1.2). Since the goal is to have the UAV follow a route

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the radius of the transition circles should not have a radius smaller than the minimum turn radius of the UAV.

The turn radius of an aircraft is also dependent on the wind speed and wind direction. The operator might have an idea of the current weather situation when putting the UAV in the air, but the conditions may change. In the case of a stronger wind it would mean the UAV might not be able to make turns with the turn radius that was set beforehand. Even if the operator would have perfect knowledge of the current weather situation, a strong wind still influences the flight path of the UAV (Osborne & Rysdyk, 2005). The wind module deals with these situations by checking if the UAV needs a bank angle near the maximum bank angle based on current information about the turn radius, cruise speed, wind speed and wind direction.

2.3.1 Implementation

The wind module tries to handle situations where there is a lot of wind and the UAV is not able to complete its turns anymore by updating the radius of the transition circles based on the larger turn radius of the UAV. The module continuously calculates the bank angle that is needed to make a turn with a given radius, based on current information about cruise speed, wind speed and wind direction. If it is found the bank angle that is needed to complete a turn is greater than the maximum bank angle of the UAV, the radius of the transition circles is updated. The new radius depends on the current wind conditions. A stronger wind will lead to a larger adjustment in the radius of the transitions circles (see also Formule 2.3). When the radius of the transition circles is updated, a route re-plan is triggered to incorporate this new value of the parameter in the route. The Flightgear simulator allows weather scenarios to be created by the user (see Section 2.1.1). These scenarios also allow wind speed and direction to be set. These options are used to simulate (strong) winds on which the wind module should react.

2.3.2 Regulative Control

The control problem of dealing with the influences of wind on the turn radius of the UAV does not fit well into any specific level of the control sophistication hierarchy. Instead, it deals with problems found in both the levels Aviate and Flight Control (route planning and wind, respectively). Also, the task of the wind module is regulative in nature. Based on the current weather situation the UAV is in the control of the UAV should be regulated in order for the UAV to fly its mission successfully.

2.3.3 Bank Angle, Wind Speed and Direction, Cruise Speed and Turn Radius

The bank angle required to fly a circle with a given radius depends on a number of factors, two of which are the wind speed and wind direction. Having a
changing wind direction with respect to the heading of the aircraft influences the required bank angle. When the aircraft has a downwind heading the wind can ‘push’ the aircraft out of the circle, while with an upwind heading of the aircraft the wind can ‘push’ the aircraft in the circle. The graph in Figure 2.11 displays this idea. In this figure the bank angle is displayed as a function of the heading of the aircraft with respect to the wind direction. When the aircraft has an upwind heading (i.e. 0 degrees in Figure 2.11), only a shallow bank is needed (i.e. about 20 degrees in Figure 2.11). A downwind heading of the aircraft (i.e. 180 degrees in Figure 2.11) leads to a steep bank (i.e. about 75 degrees in Figure 2.11).

The idea as displayed in Figure 2.11 is captured by the following formulas. The bank angle in degrees given a wind speed, cruise speed and turn radius can be calculated with Formula 2.2.

\[
\phi = \arctan\left(\frac{V_{cr}^2}{g \cdot R_{gr}}\right) \cdot \frac{180}{\pi}
\]

(2.2)

\(\phi\) = bank angle in degrees

\(R_{gr}\) = turn radius in meters

\(V_{cr}\) = cruise speed in m/s

\(w_{speed}\) = wind speed in m/s
\( w_{\text{dir}} \) = wind direction in degrees relative to UAV

\( g \) = standard gravity (\( \simeq 9.81 \))

\[
V_{gr} = \sqrt{(V_{cr} + w_{\text{par}})^2 + w_{\text{perp}}^2}
\]

\[
w_{\text{par}} = -w_{\text{speed}} \times \cos(w_{\text{dir}} \times \frac{\pi}{180})
\]

\[
w_{\text{perp}} = -w_{\text{speed}} \times \sin(w_{\text{dir}} \times \frac{\pi}{180})
\]

Rewriting this formula to obtain the turn radius given the bank angle, wind speed and cruise speed leads to Formula 2.3.

\[
R_{gr} = \frac{V_{gr}^2}{g \times \tan(\frac{\pi \phi}{180})}
\] (2.3)

This formula is used to calculate the new radius of the transitions circles. The bank angle used in this formula is set to 30 degrees, which is less than the 35 degrees that is set as the maximum bank angle by the autopilot. This is done for two reasons. The first reason is that Formula 2.2 underestimates the true bank angle of the UAV (see Section 3.2.1). The second reason is to ensure the UAV will not have to fly directly at its maximum after a new turn radius has been calculated.

2.4 Location Module

During flight the UAV might encounter interesting locations. Here the term interesting can refer to anything that is of interest to the current mission. In the case of the location module an interesting location refers to zones that the UAV should not fly in. Examples of such zones are zones that are dangerous to fly in (e.g. in case of fire there might be smoke in the air), contain unforeseen objects (e.g. a building site with tall cranes) or contain moving objects (e.g. other UAVs). These kind of zones are from here on referred to as dangerous zones. The aviate level in the control sophistication hierarchy also deals with obstacle avoidance and no-fly zones. There is some similarity, but the difference is that the obstacles and no-fly zones in the aviate level are already known to be there during route planning, while the dangerous zones are only encountered during flight. The route planning algorithm can take into account the (static) objects and no-fly zones. The dangerous zones are only detected when the UAV is in the air, executing its mission. This is also referred to as situational awareness (Suresh & Ghose, 2010; de Wagter & Mulder, 2005).

2.4.1 Implementation

The location module continuously monitors the environment of the UAV looking for dangerous locations. In the current implementation a rectangular dangerous zone is defined by its GPS coordinates (see Figure 2.12a). The dangerous zone is
not directly visible on the map, but becomes visible after a given amount of time. Based on the current location of the UAV the location module can determine whether or not the UAV is flying in a dangerous zone. When a dangerous zone is entered, the module adds a new waypoint to the route and triggers a route re-plan as to get a new route around the dangerous location (see Figure 2.12b). The location of the new waypoint is hard-coded (see Section 2.5.3). The same holds for the location of the dangerous zone (see Section 2.5.3). When it is found the UAV still flies through the dangerous zone even though the new waypoint has been added, the location of the new waypoint is adjusted. The adjustment of the new waypoint is towards the north-west, in small steps. The longer the UAV flies in the dangerous zone, the larger the adjustment steps become. This is captured in Formulas 2.4 and 2.4.1.

\[
\begin{align*}
\text{lon} &= \text{lon} - 0.007 + \max(0.0045, n \times 0.0001) \\
\text{lat} &= \text{lat} + 0.007 - \max(0.0045, n \times 0.0001)
\end{align*}
\]

\( \text{lon} \) = longitude

\( \text{lat} \) = latitude

\( n \) = time in dangerous zone

Future implementations of the location module should not rely on the GPS location of the UAV, since this assumes the location of the dangerous zone is already known; the detection of the dangerous zone is simplified in the current implementation of the location module. A more realistic implementation would rely on image processing of the on-board camera of the UAV (Merino et al., 2005). The Flightgear package does not directly support capturing the video feed from the on-board camera (nor from any other video feed). However, given the open-source nature of Flightgear, one should be able to obtain this feed.

Another point for future implementation is that the module should not add a waypoint by itself, but instead rely on the obstacle avoidance functionality in the route planning algorithm as defined by the Aviate level. The dangerous zone can then be added as an obstacle and the route planning algorithm will then plan a route around the dangerous zone. The problem is that the obstacle avoidance functionality is not yet available in the Flightgear project. A second problem is that route re-planning is more computationally expensive than local re-planning and might not always be necessary (Scherer, Singh, Chamberlain, & Elgersma, 2008).

### 2.4.2 Regulative Control

The dynamic nature of the dangerous zones (i.e. the zones can only be detected in flight) makes it an ideal candidate to be handled by a module in the regulative control component. The module continuously checks for dangerous zones and when it finds one the control of the UAV is regulated by adding a new waypoint
and triggering a re-plan of the route. To add the new waypoint and trigger a re-plan the module needs its connections to the different levels of the control sophistication hierarchy.

2.5 Parameter Settings

The parameter settings as used by the simulator, autopilot and GCS are described in the following sections.

2.5.1 Flightgear

During testing of the location module no wind is added to the simulated environment. Testing the wind module leads to a setting of 30 knots (55 km/h) for wind speed, with a 180 degree wind direction setting. These settings are derived from tests with the UAV and Flightgear. See also Section 3.2.1. Tests are started when the UAV has completed one full round along the route. This is done to have the UAV stabilize its flight.

2.5.2 Autopilot

The speed of the UAV is set to 100 knots (185 km/h), with a maximum of 300 knots and a minimum of 20 knots (i.e. the PID controller will not send airspeed command out of the [20, 300] interval). The altitude of the UAV is set to 200 feet (61 meters). The maximum bank angle of the UAV is set to 35 degrees.
<table>
<thead>
<tr>
<th>Waypoint</th>
<th>GPS (latitude; longitude)</th>
<th>Altitude (feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>51.9899543; 4.38114166</td>
<td>200</td>
</tr>
<tr>
<td>2</td>
<td>51.9504017; 4.42165375</td>
<td>200</td>
</tr>
<tr>
<td>3</td>
<td>51.9757871; 4.48688507</td>
<td>200</td>
</tr>
<tr>
<td>4</td>
<td>52.0142608; 4.43847656</td>
<td>200</td>
</tr>
<tr>
<td>5</td>
<td>52.0116200; 4.40165500</td>
<td>200</td>
</tr>
</tbody>
</table>

Table 2.1: Waypoints in terms of GPS coordinates and altitude.

2.5.3 Ground Control Station

The default radius of the circles used in route construction is set to a safe 1600 meters. In testing the wind module this radius is adjusted to 700 meters, since 1600 meters would be too great a radius for the wind to have any disturbing effects.

Coordinates

The standard route the UAV was commanded to fly is displayed in Figure 2.3. The GPS coordinates of the route are displayed in Table 2.1. The first four waypoints in the table correspond to the four waypoints as displayed in Figure 2.3. The waypoints are numbered counterclockwise, starting with the bottom left waypoint. Waypoint 5 is the waypoint that is added by the Location module (see Section 2.4) when a dangerous zone is detected.

The dangerous zone is defined by a rectangle. The top-left corner is given by the longitude-latitude coordinates: (52.0096120; 4.3959050) and the bottom-right corner is given by: (51.9898490; 4.4280050).

2.5.4 Regulative Components

The regulative component contains two modules: the wind module (Section 2.3) and the location module (Section 2.4). The wind module is the first on the list of modules and is therefore executed first in each ‘control-loop’ of the UAV. Subsequently, the location module is executed.
Chapter 3

Results

This chapter will give an overview of the results of testing the regulative modules in the Aoife project. First an analysis is made of the relation between the control sophistication hierarchy and the Aoife project (Section 3.1). Next the results for the wind module (Section 3.2) and location module (Section 2.3) are discussed. For each module the relevant levels, parameters and functionality is identified with respect to the control sophistication hierarchy.

3.1 Control Sophistication in Aoife

An analysis is made of how the parameters and functionality found in the Aoife project belong to the different levels in the control sophistication hierarchy (see Figure 2.9a). The analysis makes it easy to identify the different levels, parameters and functionality a regulative module needs access to in order to work properly. The result of the analysis is displayed in Figure 3.1. The figure shows that the levels Joint Mission and Mission are not (yet) fully implemented in the Aoife project. For the Mission level the implicit mission objective is to observe a location by using a camera. At a later stage in development the project should support other mission objectives as well. Whenever a mission element changes, the navigate level gets a message from the Mission level. Based on this message the current flight plan can be adjusted, or, when necessary, a new flight plan can be constructed. In the Navigate level the waypoints and track-segments are found as well as the cross-track error. Whenever the Navigate level needs to change the flight plan or a track segment, a message is sent to the Aviate level. The Aviate level is concerned with the route construction. This is also the place where the maximum bank angle parameter is found. The current implementation assumes that there are no obstacles between waypoints and a route is thus easily constructed. Future implementation should take obstacles into account. The Flight Control level makes the UAV fly. The UAV is controlled by the pitch, roll and throttle parameters. The PID-controllers can also be modified at this level. The PID-controllers have parameter for the gains (see Formula 2.1) and
for the minimum and maximum output value. The last level, the Flight level, deals with the UAV itself. The Flightgear simulator takes care of this part.

### 3.2 Wind Module

The wind module continuously monitors the weather conditions (more specifically: the wind conditions) in the current environment of the UAV and tries to determine whether or not the given route can be flown in these conditions. When there is a strong wind, for example, the UAV might not be able to make a turn and follow its route, because the bank angle of the UAV is limited and the wind blows the UAV off track. The wind module adjusts the route by increasing the radius of the transition circles to such a degree that the UAV can safely follow its route again.

This section describes the results of this wind module. First the usability of Formula 2.2 for estimating the bank angle of the UAV is tested. Based on these results the conditions are chosen in which the wind module will be tested. Next the wind module is tested in simulation. The section concludes by identifying the relevant levels in the control sophistication hierarchy for this wind module.
3.2.1 Bank angles

Simulation results are gathered to see what weather conditions are suitable for testing the wind module in. The weather conditions need to push the UAV to its maximum bank angle. Under these conditions the wind module will be active and can then be tested. The conditions are then used to test how well Formula 2.2 performs as an indicator for the bank angle of the UAV. A difference between the formula and values observed in reality is expected. Since the wind module will adjust the route based on Formula 2.2 it is important to check how large this difference is and whether or not the formula is still usable in the wind module.

The results for determining what weather conditions are suitable for testing the wind module in are displayed in Table 3.1. The corners correspond to the corners as found in Figure 2.3, starting from the bottom-left corner and counting counterclockwise. For each corner the average bank angle over 3 trials is calculated for different wind speeds. Note that the bank angle of the UAV changes during the corner and only the maximum bank angle is recorded per trial. The wind direction is held constant at 180 degrees (i.e. blowing from the south) and the radius of the transition circles is set to 750 meters. As can be seen in the table, when the wind speed is set to 30 knots or higher the maximum bank angle (i.e. 35.0 degrees) is reached in corner 2 and, for the 30 knots wind speed case, in corner 3. One would expect that corner 3 with a wind setting of 50 knots would also make the UAV bank at its maximum bank angle, but the data shows this is not the case. The difference is due to the rather extreme wind speed of 50 knots. The UAV is already banking inward when it enters the corner to counteract the strong wind that blows the UAV off track. The UAV then quickly banks a bit more to make the turn and then reaches an orientation where the wind helps the UAV through the corner. Compared to the 30 knots condition the UAV does not bank inwards when it enters the corner and therefore needs more time to reach the required bank angle. This results in a larger of overshoot of the corner (see Section 2.1.3) which then results in a larger bank angle to compensate for this overshoot.

The data shows that with a wind setting of 30 knots the UAV banks at its maximum angle in two of the four corners. This would be a situation where the wind module should step in by recalculating and updating the radius of the transition circles and trigger a re-planning of the route. The data also shows that with a wind setting of 50 knots, only one corner pushes the UAV to its maximum bank angle (i.e. corner 2). Based on these results the wind conditions are set to a speed 30 knots, blowing from the south (Section 2.5.1).

By using Formula 2.2 the expected bank angles for a given wind speed can be calculated. The turn radius \( R_{gr} \) is set to 750 meters and the cruise speed, \( V_{cr} \), to 100 knots. The wind speed (\( w_{speed} \)) and direction (\( w_{dir} \)) are the variables. The results can be found in Table 3.2. Note that the values in the column ‘Wind Direction’ are based on the change of wind direction relative to the UAV during its banked flight in the corner. The values in Table 3.2 are not the same as the values in Table 3.1, although they are based on the same parameters. One
observation is that the values as calculated by Formula 2.2 are never higher than the values found in simulation. The only exception here is corner 2 at 50 knots and a bank angle of 39.0 degrees, which is higher than the 35.0 degrees observed in simulation for the same corner and same wind speed. However, 35.0 degrees is the maximum bank angle the UAV is allowed to fly due to safety measures. Bank angles higher than 35.0 degrees should thus be read as being 35.0 degrees, which means the observation that the calculated bank angles are never higher than the observed bank angles still holds. Another observation is that the values in Table 3.2 follow the same trend as the values found in simulation. For each wind speed case corner 4 requires the shallowest bank angle, while corner 2 requires the steepest bank angle. Corners 1 and 3 have bank angles that are in between the bank angles of corner 2 and 4, with corner 3 having a slightly higher bank angle than corner 1.

The differences between the values from Table 3.1 and Table 3.2 can be explained by the fact that the autopilot of the UAV relies on PID-controllers to stay on track (see Section 2.1.3). The autopilot tries to minimize the cross-track error (XTE) by using PID-controllers to control the bank angle of the UAV. This also means the UAV will only bank when there is a XTE; the autopilot reacts to deviations from the route. When a corner is coming up in the route the UAV will first overshoot the corner. The PID-controllers then detect the XTE is becoming too large and make the UAV bank into the corner. However, since there was a bit of overshoot the UAV will need to compensate by making a steeper bank. When the corner is entered slight oscillations due to overshoot will also make the UAV bank a bit more extreme than would be expected from Formula 2.2.

The underestimation of the bank angle by Formula 2.2 suggests the wind module should not wait for the calculated bank angle to reach the maximum bank angle of the UAV since then it would already be too late for the wind module to make appropriate adjustments. Instead the wind module should react a bit earlier. The threshold for when the wind module should react is set to 85% of the maximum bank angle of the UAV. With a maximum bank angle of 35 degrees this means the wind module will react when the calculated bank angle exceeds 29.75 degrees. Looking at the values in Table 3.2 both the wind speed settings of 30 knots and 50 knots will lead the wind module to adjust the radius of the transition circles.

### 3.2.2 Simulation results

The wind module is tested in simulation. A brief overview of the most relevant parameters is given here and the full overview of all parameter settings can be found in Section 2.5. The radius of the transition circles is set to 700 meters. Wind speed is set to 30 knots with a direction of 180 degrees. The maximum bank angle of the UAV is 35 degrees. The simulations show positive results with respect to the usability of the wind module. Without the wind module the UAV needs to bank at its maximum angle in two of the four corners (see Table 3.3). Activating the wind module leads to an updated route with the radius of the
Table 3.1: Bank angles of the UAV (in degrees) for the four corners with varying wind speeds (in knots). The wind direction is held constant at 180 degrees.

<table>
<thead>
<tr>
<th>Corner</th>
<th>Wind Direction</th>
<th>Wind speeds (knots)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0 kt</td>
</tr>
<tr>
<td>1</td>
<td>270</td>
<td>19.8</td>
</tr>
<tr>
<td>2</td>
<td>180</td>
<td>19.8</td>
</tr>
<tr>
<td>3</td>
<td>110</td>
<td>19.8</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>19.8</td>
</tr>
</tbody>
</table>

Table 3.2: Calculated bank angles (in degrees) by using Formula 2.2 for the four corners with varying wind speeds (in knots). The wind direction column represents the direction of the wind with respect to the heading of the UAV.

<table>
<thead>
<tr>
<th>Corner</th>
<th>Wind Direction</th>
<th>Wind speeds (knots)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0 kt</td>
</tr>
<tr>
<td>1</td>
<td>25.8</td>
<td>20.8</td>
</tr>
<tr>
<td>2</td>
<td>25.7</td>
<td>32.3</td>
</tr>
<tr>
<td>3</td>
<td>26.1</td>
<td>31.9</td>
</tr>
<tr>
<td>4</td>
<td>25.8</td>
<td>19.7</td>
</tr>
</tbody>
</table>

transitions circles set to 786 meters. This is an increase of 86 meters in radius. The adjustment happens when the UAV enters the second turn. Here the wind module detects the bank angle will be greater than 29.75 degrees and Formula 2.3 is used to calculate the new turn radius. The new bank angles are displayed in Table 3.3. The results show the UAV will not need to bank at its maximum angle anymore in corners 2 and 3.

One issue with the reactive nature of the wind module (i.e. the module only reacts based on the current situation) is that there is no information about the rest of the route. One case in which this results in suboptimal behavior is when the corners on a route are positioned in such a way that the bank angle needs to get steeper with each corner. An example of such a route is displayed in Table

<table>
<thead>
<tr>
<th>Corners</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind Module</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

Table 3.3: The bank angles (in degrees) for the different corners under two conditions: a de-activated wind module (Off) and an activated wind module (On). The wind speed is held constant at 30 knots with a direction of 180 degrees.
Table 3.4: Example of a route where the wind module needs to react multiple times. For each relative wind direction the bank angle is calculated. The turn radius (T.R.) is calculated in the column ‘New T.R.’. Whenever the bang angle exceeds 29.75 degrees the turn radius is updated with the calculated turn radius.

<table>
<thead>
<tr>
<th>Corner</th>
<th>Heading</th>
<th>Rel. Wind Dir.</th>
<th>Bank Angle</th>
<th>T.R.</th>
<th>New T.R.</th>
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3.4, with the assumption that the wind blows from the south. In this table the heading of the UAV is indicated together with the relative wind direction. For each relative wind direction the bank angle and turn radius are calculated by using Formula 2.2 and Formula 2.3, respectively. Whenever the bank angle exceeds 29.75 degrees (see Section 3.2.1) the radius of the transition circles is updated with the calculated turn radius. The route makes the UAV turn to a downwind heading over the course of a few turns. As can be seen in Table 3.4 corners 1 and 2 are corners the UAV can easily make within the bounds of its maximum bank angle. At corner 3 the turn radius gets updated to 768 meters. Then the issue of the reactive nature of the wind module becomes apparent: at corner 4 the turn radius needs to be updated again, since the UAV is still banking too much.

3.2.3 Regulative Control

Based on the analysis made in Section 3.1, the relevant levels, parameters and functionality for the wind module can be determined. One of the parameters the wind module is concerned with is the maximum bank angle. This parameter can be found in the Flight Control level. When necessary, the module changes the radius of the transition circles and triggers a route re-plan. Both the radius parameter and the route planning functionality can be found in the Aviate level. Then when the route is updated, there is some bookkeeping the module needs to take care of: the active track segment should be set to the ‘new’ segment that connects to the new waypoint. This is done in the Navigate level.

3.3 Location Module

The location module monitors the environment of the UAV and tries to detect and avoid dangerous zones. Dangerous zones can only be detected during flight: they are not known to be present in advance during the route planning phase. Whenever a dangerous zone is detected, the zone is added to the map (i.e. the operator can see that a dangerous zone has been detected) and the location
module takes appropriate actions to avoid the dangerous zone. The current implementation lacks a realistic form of dangerous zone detection in the sense that dangerous zones are only detected when the UAV flies directly above one (see Section 2.4.1). Although future implementation should focus on making this detection more realistic, the idea of dangerous zones and the reaction of the location module remains the same.

The following sections show the simulation results of the location module (Section 3.3.1) and link the location module to the levels and functionality in the control sophistication hierarchy (Section 3.3.2).

3.3.1 Simulation results

An example of how a dangerous zone is displayed in the GSC is given in Figure 2.12a. The reaction of the location module to avoid the dangerous zone is displayed in Figure 2.12b. A more close-up view of the reaction of the location module is given in Figure 3.2. In Figure 3.2a the UAV approaches the dangerous zone. As can be seen in the image the route goes directly through the dangerous zone. In Figure 3.2b the UAV entered the dangerous zone. The location module added a new waypoint to the route (the waypoint is displayed on the left side in Figure 3.2b, above the dangerous zone) and triggered a route re-plan. The location of the new waypoint is set beforehand and the exact location of the waypoint can be found in Table 2.1. The UAV is now turning towards the new route. The change in heading the UAV makes to get back on route is quite large. Due to this large change in heading and the fact that the PID controllers are a bit slow to react when the UAV comes near its route the UAV overshoots the route. As can be seen in Figure 3.2c the UAV overshoots the route by quite a bit and the UAV will oscillate over the route for a short while (see also Section 2.1.3). The UAV will still cross the dangerous zone when it follows the route, as can be observed in Figure 3.2c. The new waypoint did not make the route completely avoid the dangerous zone. When the UAV enters the dangerous zone again, the waypoint that was added by the location module now gets adjusted to a north-west direction. The result of the adjustment can be found in Figure 3.2d. The formulas to calculate the adjustments are given in Formulas 2.4 and 2.4.1. Here \( n = 1 \), since the UAV only crosses the no-fly zone for a short amount of time. When looking very closely the route still crosses the dangerous zone after this adjustment. However, the amount of time the UAV will be in the dangerous zone is too small for the location module to adjust the waypoint again.

One observation that one can make based on Figure 3.2b is that the UAV is already flying in the dangerous zone when the location module makes its adjustments. This might seem a bit late given that the UAV is then already flying in the dangerous zone. The slow reaction is largely due to the fact that no proper detection method has been implemented: a dangerous zone is only detected when the UAV flies directly above one. On the other hand, the UAV might not always be able to detect a dangerous zone in advance and then the situation as described here is quite realistic. In this situation the UAV needs to
(a) The UAV is approaching the dangerous zone. The location module has not made any modifications to the route yet.

(b) The UAV is turning towards the new route. The location module added a new waypoint and triggered a route re-plan.

(c) Due to the large change in route, the UAV makes a quite drastic turn towards the new route. This results in overshoot for which the UAV needs to correct.

(d) The addition of a new waypoint at the given location is not sufficient to lead the route around the dangerous zone. The location of the waypoint is adjusted to a more north-west location.

Figure 3.2: The location module in action.

3.3.2 Regulative Control

The relevant levels, parameters and functionality for the location module are identified by using the analysis made in Section 3.1. When a dangerous zone is detected a new waypoint is added to the route. The waypoints can be found in the Navigate level. Then a route re-plan needs to be triggered that takes into account the new waypoint. This functionality can be found in the Aviate level. Adjustments of waypoints work in the same way. In the current implementation the location module also needs to be aware of the location of the UAV which can be extracted from the Navigate level.

Future implementation of the location module might need access to the on-board camera of the UAV. The module then probably also needs access to the Flight Control level.
Chapter 4

Discussion

In this chapter the results are discussed for the wind module (Section 4.1) and location module (Section 4.2). The results for regulative control in general and in the context of the Aoife project (Sections 4.3 and 4.3.1) are also discussed. Next a direct answer to the research questions is given (Section 4.4). The chapter concludes with ideas for future research (Section 4.5).

4.1 Wind Module

The wind module monitors the wind conditions the UAV is in and, when necessary, adjusts the route in such a way that the UAV can safely fly in these wind conditions. The results of the wind module show that the module is usable in practice. Based on the current wind conditions the wind module may update the parameter that defines the turn radius of the transition circles. This only happens when it is found the wind conditions (i.e. wind speed and direction) are too strong for the UAV to be able to follow its route. The results also show that Formula 2.2 predicts the bank angle well enough for the wind module to be useful. The calculated bank angles and the actual bank angles as given in Table 3.1 and Table 3.2 are summarized in Table 4.1. As can be seen in this table there are some differences in calculated bank angle and the actual bank angle. This is largely due to the use of PID-controllers in the UAV, which makes the UAV a bit slow to react to route changes.

4.1.1 Discussion and Future Work

One point of improvement for the wind module can be found in taking the planned route into account when updating the radius of the transition circles. In the current implementation of the wind module the planned route is ignored, which might lead to a situation where the wind module needs to update the route multiple times. This effect can be observed in Table 3.4. Another point of improvement is the use of sensor readings for determining the wind speed and
Corners

<table>
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</table>

Table 4.1: The calculated bank angles and actual bank angles from Table 3.2 and Table 3.3 summarized.

direction. It is now assumed the wind speed and direction are given through sensor readings, while not all UAVs carry these sensors (e.g., lightweight UAVs). A future implementation of the wind module should use methods to calculate the wind speed and direction from other sensor readings (e.g., Langelaan, Nicholas, & Neidhoefer, 2010). It should be noted that such methods will introduce a source of noise.

4.2 Location Module

The location module monitors the environment of the UAV and tries to detect dangerous zones that are not known beforehand (i.e., the operator is not aware of these zones during planning of the mission). When a dangerous zone is detected, the module tries to avoid the zone by leading the route of the UAV around it. The idea of the location module is also usable in practice. Building sites with tall cranes or smoke coming from a forest fire can be identified as dangerous zones. The results of the location module show that the module behaves as expected. When the module detects a dangerous zone, a route re-plan is triggered so that the dangerous zone is avoided. The UAV will make quite a large adjustment in its heading to get back on its (new) route. The addition of the waypoint may not lead the UAV completely around the dangerous zone. If this is the case, the newly added waypoint is moved to a north-west direction.

4.2.1 Discussion and Future Work

A point of improvement in the location module is the detection mechanism for dangerous zones. The module now relies on GPS coordinates of both the dangerous zone and the UAV. It would be more realistic to detect dangerous zones based on sensor readings (e.g., image processing of the camera feed). Another improvement can be found in the re-routing of the UAV. The current implementation assumes a rectangular shape of the dangerous zone and has a new waypoint hard-coded to re-route the UAV. To be useful in practice the module should find a new waypoint based on the location and shape of the dangerous zone. Related to this point is the lack of obstacle avoidance in the route planning algorithm. An implementation of obstacle avoidance would change the working of the location module in the sense that it does not need to think about how to re-route the UAV; simply indicating where a dangerous zone is found.
would suffice. Having a more advanced route planning algorithm that incorporates obstacle avoidance is desirable (Amelink, 2010) and makes the avoidance of dangerous zones also easier.

4.3 Regulative Control

The idea of regulative control is applied to the field of UAVs. The control sophistication hierarchy is extended by a component that provides an overview of the levels in the hierarchy. This component makes the integration of new functionality that does not fit into a specific level of the control sophistication more intuitive. Functionality that needs access to parameters or functionality on multiple levels in the hierarchy also benefits from this regulative component.

The regulative component is not a learning component or black box as it was the case in Lagarde et al. (2010). The use cases and safety regulations of UAVs make it undesirable for a UAV to perform actions without having the operator know what is going on. The operator must be able to understand the actions the UAV takes. Therefore the regulative component only serves as a container for modules. The modules must have clearly specified behavior or inform the operator about the state it is currently in.

4.3.1 Regulative Control in Aoife

The results of the separate modules show that regulative control is feasible in the Aoife project. The analysis of the Aoife project in terms of the six levels of control sophistication shows that the parameters and functionality of the Aoife project are separated over the different levels (see Figure 3.1). The implementation of the wind and location module shows that both modules need access to the different levels in the hierarchy in order to work properly. The regulative component provides this access.

The analysis of the Aoife project with respect to the control sophistication hierarchy also shows that there is functionality missing in the Aoife project. Especially in the higher levels of the hierarchy (i.e. Mission and Joint Mission) the functionality is not as rich as desired. The regulative component would be even more useful when this functionality is implemented. With new functionality in the higher levels, other functionality might be thought of that needs access to multiple levels in the hierarchy. The regulative component could provide this access.

4.3.2 Discussion

A criticism with regard to regulative control in general is that the introduction of regulative control in a hierarchical controller interferes with the hierarchical structure; the ordered structure disappears by adding connections to all the layers in the hierarchy (see Figure 2.8b). The idea of hierarchical control,
where there is a clearly specified control flow, is indeed broken by the regulative component. The regulative component breaks into the control flow of the hierarchical structure. One could argue this is an ‘ugly’ solution and that the hierarchical structure should be left intact. However, the purpose of regulative control is to increase functionality of the hierarchical system, without adding new layers. Adding new layers to the hierarchical structure is also possible, but only to a limited extend. Due to the large number of interactions between layers only relatively small hierarchical structures are feasible (Wareham et al., 2011). The hierarchical structure itself also remains intact: layers are not removed and connections are not modified.

Another point of discussion is that regulative control merely adds a new layer (or multiple layers) to the hierarchical structure. The regulative component in Figure 2.8b, for example, could also be drawn as a new layer on top of all the other layers. While this might seem true at first, the working of the regulative component is different from that of the layers in the hierarchical system. The regulative component introduces connections to all the layers in the hierarchical structure. The hierarchical structure has a clearly defined control flow (see Figure 2.9a) and the new connections allow the regulative component to break into this control flow. The breaking into the control flow of the hierarchical structure has the advantage that the regulative component can change parameters on low layers in the hierarchy, which will influence the output of higher layers.

4.4 Research Questions

The previous chapters discussed the implementation of a regulative component in the field of UAVs. The regulative component found its inspiration in regulative control, but differs in the fact that there is no reactive behavior involved. The Aoife project was used to implement and test the ideas of this thesis with respect to regulative control. The control sophistication hierarchy was extended by a regulative component. Two modules were implemented to test the regulative component: a wind module and a location module. Both modules regulate control of the UAV on multiple levels in the control sophistication hierarchy. The wind module is more involved with the Aviate level, while the location module is more focussed on the Navigate level. The ideas of the modules are also usable in practice, although some modifications are needed before real-world use is possible.

The following sections will focus on answering the research questions directly. Both research questions are answered separately (Section 4.4.1 and 4.4.2).

4.4.1 Research Question 1

The first research question is as follows:

How does regulative control fit into the field of UAVs?

Regulative control as proposed by Haselager et al. (2008) and van Dijk et al. (2008) is not directly applicable to the field of UAVs. The absence of a reactive
control structure makes it difficult to implement regulative control. Regulative control was therefore only used as a source of inspiration for implementing a regulative component in the Aoife project. The regulative component extends the control sophistication hierarchy and has access to all the levels of the hierarchy (see Figure 2.9b). The access to all the levels of the hierarchy means the regulative component can read and adjust parameters and use and trigger functionality. By changing parameters and triggering functionality the working of the hierarchy is changed.

In comparison to the original idea of regulative control, the regulative component still is regulating the working of the hierarchy. The approach, however, is quite different. In the original idea of regulative control a reactive structure would be regulated. Behavior would be inhibited without breaking the overall functionality of the agent\(^1\) itself. Even stronger: by inhibiting specific behavior in certain situations, new behavior can emerge (Lagarde et al., 2010). The control structure in the Aoife project is not reactive in nature. Inhibiting behavior would result in malfunctioning of the UAV. It is also not desirable from the point of view of operators and safety guidelines to have new, unexpected behavior emerge from a regulative component. This also means the regulative component cannot be a black box like was the case in Lagarde et al. (2010). The behavior of the regulative component (i.e. the modules that are added to the component) needs to be clearly specified and/or make it very clear to the operator what is going on.

To summarize, the answer to research question 1 is as follows: regulative does not directly fit into the field of UAVs, but the ideas of regulative control are usable for implementing a regulative component. The hierarchical control structure in UAVs is extended by a regulative component that regulates the control flow of the hierarchical structure by reading and adjusting parameters and triggering functionality.

4.4.2 Research Question 2

The second research question is as follows:

Is regulative control feasible in the complex dynamics of UAVs?

The feasibility of regulative control in highly complex environments with respect to the field of UAVs has been shown by implementing two modules. Although the original form of regulative control is not implemented, as mentioned before, the idea of regulative control is maintained. The two modules works as expected. The wind module monitors the environment and adjusts the route of the UAV when the current wind situation would blow the UAV of track. The location module keeps track of the environment by detecting dangerous zones. When a dangerous zone is detected the module re-routes the UAV around this zone. The results have shown that the modules works as expected, although there is still room for improvement.

\(^1\)Agent refers to the entity, or robot, that is being controlled.
The complexity of implementing modules can be kept low. By clearly specifying the parameters and functionality in each of the levels of the control sophistication hierarchy (see Figure 3.1), it is fairly easy to determine the relevant parameters and functionality for a module.

A point related to the complexity of the environment is the complexity of the behaviors of the modules. The behaviors need to be understandable by an operator. For example, it is undesirable to adjust the route of the UAV without notifying the user that this change is made due to wind conditions. In the case of the wind module and location module it is easy to notify the operator (e.g. the location module notifies the operator through visual cues, see Figure 3.2). More complex modules are expected to be implemented that deal with the complexity of the environment and the UAV. These new modules need to have proper handling of operator notification.

To summarize, the answer to research question 2 is as follows: Regulative control is feasible in the complex dynamics of UAVs as has been shown by the implementation and testing of the two modules. One point of concern is that regulative control may break into the control flow of the UAV at any time and the behavior of the UAV may therefore be difficult to understand by the operator. Clearly defined behavior of the regulative modules and/or comprehensive notifications to the operator is required.

4.5 Future Research

Future research could focus on a number of topics. First, solving problems with the two modules in the regulative component would be of interest to UAV applications. The current implementations show some flaws that need to be fixed in order for the modules to be useful. As already discussed in Section 4.1.1 the wind module should determine the wind conditions from sensor readings that are already available on the UAV. The focus of the location module should be on the detection of dangerous zones by means other than GPS.

The Aoife project should also be developed further. The current implementation suffices to test the ideas in this thesis, but the project might be much more interesting for new research when in a more advanced state of development. The analysis in Figure 3.1 shows that the top levels of the hierarchy do not yet sophisticated if any implementation.

With respect to regulative control it has been shown that the idea of regulative control is applicable to complex environments. Due to safety regulations and the desire for behavior that is clearly defined and understandable by the operator, the regulative component cannot be a learning component. In light of new approaches to UAVs such as the BioMAV project (Gerke et al., 2011), it would be interesting to re-evaluate if and how regulative control can be applied to the control mechanisms of these biologically inspired approaches.
References


