Description of Controller Algorithms for the Autonomous Model Helicopter MARVIN

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1 Introduction

Controlling a helicopter requires specialized algorithms, which permanently have to stabilize the vehicle, as it is inherently instable. The controller described in this paper is designed especially for the autonomous helicopter MARVIN (**M**ulti-purpose **A**erial **R**obot **V**ehicle with **I**ntelligent **N**avigation) constructed at TU Berlin. It does not depend on a complete mathematical model but derives benefit from simple basic assumptions.

2 Used Controller Laws

2.1 The Desired Trajectory

In most applications, which have to deal with controlling, common PID controllers are used. The theoretical background of such a controller is well known. Only the three coefficients for P, I and D have to be defined. Figure 1 shows an example of a resulting trajectory.

For controlling an autonomous robot like a helicopter, the trajectory has to meet several constraints. For example overshooting is not allowed. If there is an obstacle shortly behind the destination position, any overshooting can lead to serious damage of the whole robot. Another point is the limitation of forces and manipulating speeds.

MARVIN uses the trajectory shown in figure 1. The desired alteration of the control deviation $e(t)$ is defined by this trajectory, which is given by

$$e(t) = C \exp(-kt) \tag{1}$$

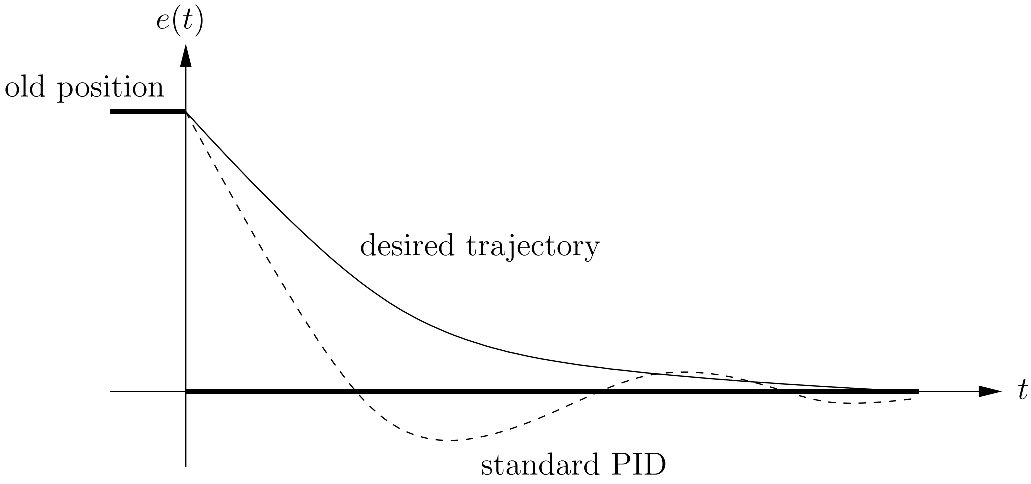

Figure 1: Comparison of usual PID response and the desired trajectory

C is a scaling factor, which will be described below. k represents the half-life period of the control deviation. This is a controller parameter.

2.2 Control Deviation vs. Manipulated Variable

In most controller tasks it is not possible to manipulate the control variable $y(t)$ directly. The manipulated variable $u(t)$ has to be altered in a different way to produce the desired trajectory for the control variable (see figure 2). At the helicopter there are two possible relationships:

$$u_1(t) \sim \dot{e}(t) \tag{2}$$
$$u_2(t) \sim \ddot{e}(t) \tag{3}$$

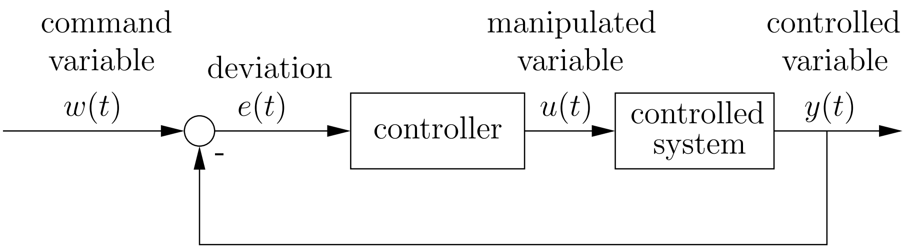

Figure 2: Control Loop

2.2.1 Case 1: $u_1(t) \sim \dot{e}(t)$

To get the necessary $u(t)$ for the first case, (1) has to be differentiated.

$$
\begin{aligned}
e(t) &= C\exp(-kt) \\
\dot{e}(t) &= -kC\exp(-kt)
\end{aligned}
$$

We define that the controller always works for $t = 0$. So we can determine the value of C:

$$
\begin{aligned}
e(0) &= C \\
\dot{e}(0) &= -kC \\
&= -ke(0) \qquad (4)
\end{aligned}
$$

Since the values at $t = 0$ can be measured, $e(0)$ is known. With the given parameter k it is possible to calculate the necessary value for $\dot{e}(0)$ to meet the desired trajectory for $e(t)$ and $y(t)$, respectively.

For future use the measurement $e(0)$ is denoted by e_0. The calculated desired output $\dot{e}(0)$ is denoted by $\dot{e}$.

2.2.2 Case 2: $u_2(t) \sim \ddot{e}(t)$

For the second case we need one more parameter in (1), so that we modify it as follows:

$$
\begin{aligned}
e(t) &= (C_1 + C_2t)\exp(-kt) \\
\dot{e}(t) &= C_2\exp(-kt) + (C_1 + C_2t)(-k)\exp(-kt) \\
&= (C_2 - kC_1 - kC_2t)\exp(-kt) \\
\ddot{e}(t) &= -kC_2\exp(-kt) + (C_2 - kC_1 - kC_2t)(-k)\exp(-kt) \\
&= (k^2C_1 - 2kC_2 + k^2C_2t)\exp(-kt)
\end{aligned}
$$

For $t = 0$ this leads to

$$
\begin{aligned}
e(0) &= C_1 \\
\dot{e}(0) &= C_2 - kC_1 \\
\ddot{e}(0) &= k^2C_1 - 2kC_2 \\
&= -k^2e(0) - 2k\dot{e}(0) \qquad (5)
\end{aligned}
$$

$\ddot{e}(0)$ is the necessary acceleration at $t = 0$ to meet the desired trajectory for $e(0)$. $e(0)$ and $\dot{e}(0)$ are current measurements.

For future use the measurements $e(0)$ and $\dot{e}(0)$ are denoted by e_0 and $\dot{e}_0$. The calculated desired output $\ddot{e}(0)$ is denoted by $\ddot{e}$.

2.2.3 Constant of Proportionality

The results for $\dot{e}$ ($\ddot{e}$, respectively) have to be transformed to u by applying a suitable constant of proportionality f. This constant is a helicopter parameter. It depends on the helicopter and can be measured. This leads to the desired output u:

$$
\begin{aligned}
u_1(e_0) &= f\dot{e} = -fke_0 && (6)\\
u_2(e_0, \dot{e}_0) &= f\ddot{e} = -fk(ke_0 + 2\dot{e}_0) && (7)
\end{aligned}
$$

2.2.4 Standard PD Controller

There is also a simple PD controller used for controlling MARVIN (with controller parameters p and d):

$$u_3(e_0, \dot{e}_0) = -pe_0 - d\dot{e}_0 \tag{8}$$

2.2.5 Comparison to standard PD controller

The controller laws (6) and (7) are similar to simple PD controllers. The coefficients can be transformed as follows:

case 1 ($u_1 \sim \dot{e}$)	case 2 ($u_2 \sim \ddot{e}$)
$P = fk$	$P = fk^2$
$D = 0$	$D = 2fk$
$k = \frac{P}{f}$	$k = \frac{2P}{D}$
$f = \frac{P}{k}$	$f = \frac{D^2}{4P}$

Because of the derivation of these equations we know the convergence characteristics very well.

2.3 Operating Point

For translation of $\dot{e}$ and $\ddot{e}$ to u we used a simple constant of proportionality f, which can be displayed as a gradient. Figure 3 depicts an additional offset Af as parameter, which can be interpreted as the operating point of this manipulated variable. Thus, the resulting output of the controller given in (6) and (7) is modified:

$$
\begin{aligned}
u'_1(e_0, \dot{e}_0) = &\quad u_1(e_0) &+A_1 f = (\dot{e} + A_1)f && (9)\\
u'_2(e_0, \dot{e}_0, \ddot{e}_0) = &\quad u_2(e_0, \dot{e}_0) &+A_2 f = (\ddot{e} + A_2)f && (10)
\end{aligned}
$$

The value of this operating point is calculated by an additional part of the controller law, an integral term. Figure 4 illustrates the calculation of A for the first case ($u \sim \dot{e}$).

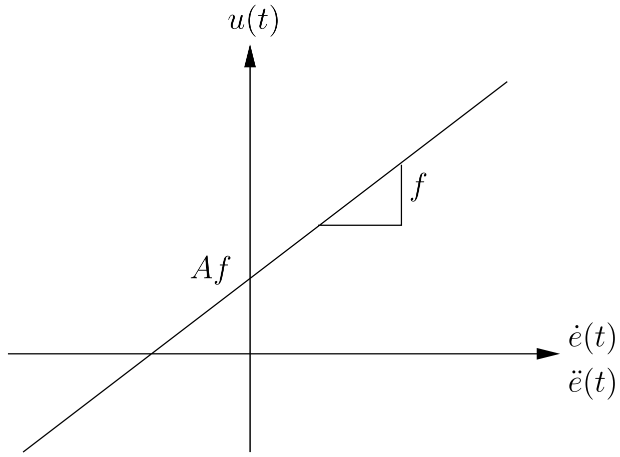

Figure 3: Proportionality combined with Operating Point

Whenever there is a difference between the measured value $\dot{e}_0$ and the desired $\dot{e}$, the operating point A is going to be changed:

$$A_1 = a\int(\dot{e} - \dot{e}_0)dt \quad (11)$$

$$A_2 = a\int(\ddot{e} - \ddot{e}_0)dt \quad (12)$$

a is another controller parameter, which affects how fast the operating point changes.

The PD controller, described in section 2.2.4, needs an integral part as well. This is necessary to eliminate remaining control deviation. The applied equation is slightly different to (9) and (10):

$$u_3'(e_0, \dot{e}_0) = u_3(e_0, \dot{e}_0) + a\int u_3(e_0, \dot{e}_0)dt \quad (13)$$

2.4 Transfer Functions

The complete controller equations look like this:

$$\begin{aligned}
u_1'(e_0, \dot{e}_0) &= (\dot{e} + A_1)f = (\dot{e} + a\int(\dot{e} - \dot{e}_0)dt)f \\
&= -(ke_0 + a\int(ke_0 + \dot{e}_0)dt)f \\
u_2'(e_0, \dot{e}_0, \ddot{e}_0) &= (\ddot{e} + A_2)f = (\ddot{e} + a\int(\ddot{e} - \ddot{e}_0)dt)f \\
&= -(k^2e_0 + 2k\dot{e}_0 + a\int(k^2e_0 + 2k\dot{e}_0 + \ddot{e}_0)dt)f \\
u_3'(e_0, \dot{e}_0) &= -(pe_0 + d\dot{e}_0 + a\int(pe_0 + d\dot{e}_0)dt)
\end{aligned}$$

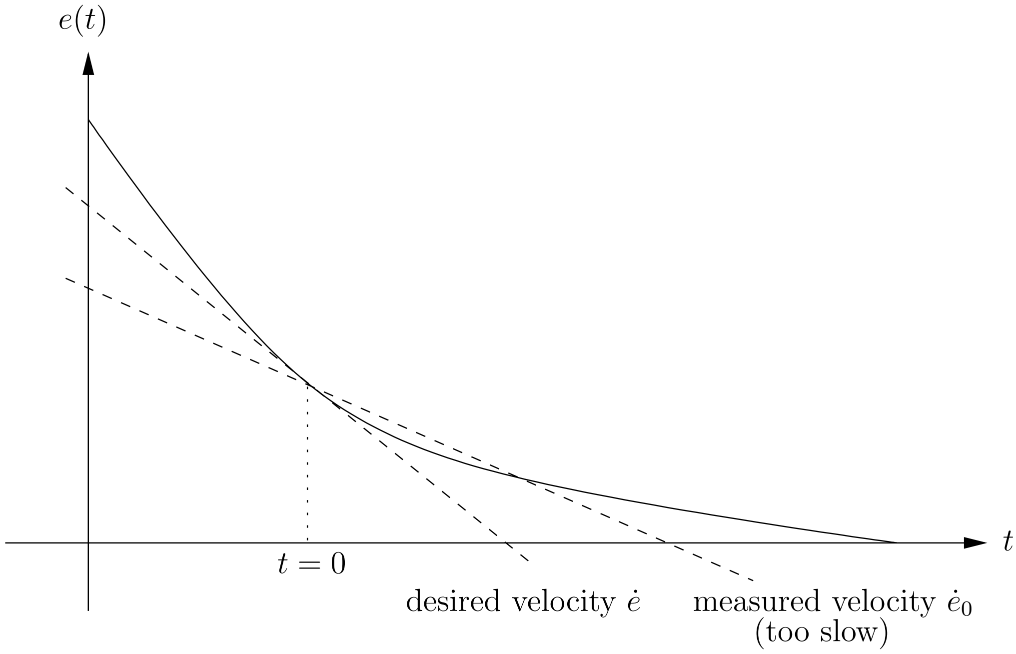

Figure 4: Determination of the Operating Point (shown for case 1)

These equations can be transformed using the Laplace Transformation with the Laplace variable s:

$$
\begin{aligned}
U_1'(s) &= -E(s)((k+a) + \frac{ak}{s})f \\
U_2'(s) &= -E(s)((k^2+2ak) + (2k+a)s + \frac{ak^2}{s})f \\
U_3'(s) &= -E(s)((p+ad) + ds + \frac{ap}{s})
\end{aligned}
$$

Now it is easy to compare the controller laws to a standard PID controller:

	case 1 ($u_1 \sim \dot{e}$)	case 2 ($u_2 \sim \ddot{e}$)	u_3
P	$k+a$	k^2+2ak	$p+ad$
I	ak	ak^2	ap
D	0	$2k+a$	d

MARVIN is controlled by normal PID controller algorithms. The difference to other applications is that the coefficients P, I and D are composed of parameters of the helicopter and of desired characteristics of movements.

3 Modifications

To improve the controlling results, there are modifications of the described controller algorithms. The two most important are described below.

3.1 Using Command Variable $w(t)$

In section 2.1 the desired trajectory of movement is described. In the following descriptions it is assumed that the command variable $w(t)$ remains constant at the new value until the destination is reached. During normal operation this is not true. Another neglected point is that at the beginning of the movement the current velocity and acceleration is zero. This means that the operating point seems to be wrong because of the difference of calculated desired velocity and the current zero velocity or acceleration, respectively (see section 2.3).

To improve the controller behavior of case 1 (section 2.2.1), the alteration of the command variable $\dot{w}(t)$ can be taken into account. Equations (6) and (9) are changed as follows:

$$\begin{aligned} u_1 &= (\dot{e} + \dot{w})f \\ u_1' &= (\dot{e} + \dot{w} + A_1)f \end{aligned} \tag{14}$$

3.2 Mixer

There are no dependencies between different controlled variables taken into account so far. For example increased collective pitch means that more engine power is required to maintain the given rotor speed. If the throttle controller does not get any information from the pitch controller, throttle will be increased only due to noticeable change of rotor speed. This leads to latency in controlling throttle.

To avoid this, the output of one controller (or any other value) can be taken into account for calculating another controller output, they are *mixed*. This value can be transformed using a suitable transfer function to meet the specific requirements. For example, the relationship between drag and pitch is not linear. Thus collective pitch has to be transformed to a new value m, which is used to change the controller output. m is simply added to the value of u':

$$u'' = u' + m \tag{15}$$

4 Application

4.1 Definitions

For controlling the flight to a new given destination, the controller uses a virtual course vector. This course is defined by the point where this movement starts and the point of the new destination (see figure 5).

There are two different coordinate systems used for calculations:

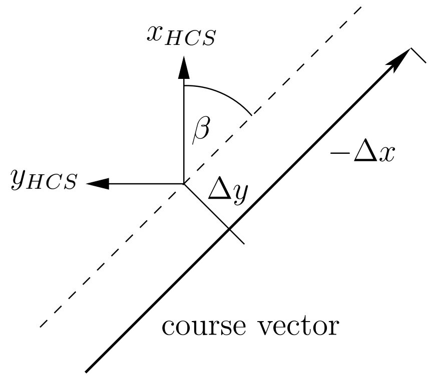

Figure 5: Definition of the course vector

BCS This is the Base Coordinate System. It is fixed in the environment (x-axis towards north, y-axis west, z-axis up).

HCS The Helicopter Coordinate System changes its point of origin and its orientation with the movement of the helicopter (x-axis forward, y-axis left, z-axis up).

4.2 Controlled Values

The described controller equations (see sections 2 and 3) are applied to several values of the helicopter. Table 1 shows these values and the used equations. The symbols are described in table 2. There are also values given for *min*, *max* and *max alteration*. These are limitations due to the mechanics and servos of the used helicopter.

4.3 Switching Controller Laws

As can be seen in table 1 for controlling φ_{ps}, φ_{qs} and P_c there are two equations used. This is necessary to deal with substantial control deviations. For P_t this is not necessary, because φ_{zs} is changed slowly according to ω_{zs} so that the deviation is always small.

If only equation (10) was used, the calculated velocity would exceed the allowed values for large deviations. To avoid this, the velocity is limited by applying equation (9) for controlling the velocity rather than position for substantial deviations. To determine which one should be used, the outputs of equations (6) and (7) are compared. The controller chooses the output, which is going to apply the smallest manipulation deflection in the primary approach direction.

Limiting the allowed velocity to $\dot{e}_s$, this is the rule for choosing the suitable equation:

$$\texttt{if}((u_1(\dot{e}_0 - \dot{e}_s) > u_2(e_0, \dot{e}_0)) \oplus (\dot{e}_s < 0)) \texttt{ then } u_2' \texttt{ else } u_1'$$

The exclusive-or operation $\oplus$ is used to take into account the correct sign, i.e. the correct direction of movement.

Controlled value	φ_{ps}		φ_{qs}		P_x	P_y	P_c		P_t	th
Equation	9	10	9	10	14	14	9	10	10	13
e_0	$\dot{\Delta x}-v_s$	Δx	$\dot{\Delta x}-v_s$	Δy	$\varphi_x - \varphi_{xs}$	$\varphi_y - \varphi_{ys}$	$v_z - v_{vs}$	$z - z_s$	$\varphi_z - \varphi_{zs}$	$\omega_r - \omega_{rs}$
w	—				φ_{xs}	φ_{ys}	—		—	—
k in $[s^{-1}]$	$\frac{300}{1024}$				$\frac{2500}{1024}$		$\frac{400}{1024}$		$\frac{1600}{1024}$	$p = \frac{500}{1024} \frac{60}{2\pi} \frac{1}{\frac{rad}{s}}$
f	$\frac{68}{1024} \frac{2\pi}{4096} \frac{rad}{\frac{mm}{s^2}}$				$\frac{1024}{1024} \frac{4096}{2\pi} \frac{1}{\frac{rad}{s}}$		$\frac{128}{1024} \frac{1}{\frac{mm}{s^2}}$		$\frac{167}{4096} \frac{4096}{2\pi} \frac{1}{\frac{rad}{s^2}}$	$d = \frac{200}{1024} \frac{60}{2\pi} \frac{s}{\frac{rad}{s}}$
a in $[s^{-1}]$	$\frac{20}{64}$				$\frac{20}{32}$		$\frac{20}{64}$		$\frac{20}{32}$	$\frac{20}{16}$
Mixer (see 4.5)	—				—		$\varphi_{xs}, \varphi_{ys}$		th	P_c
min	$-250 \frac{2\pi}{4096}$				-500		0		0	100
max	$250 \frac{2\pi}{4096}$				500		1500		1000	1100
max alteration in $[s^{-1}]$	$4 \cdot 20 \frac{2\pi}{4096}$				$50 \cdot 20$		$30 \cdot 20$		$100 \cdot 20$	$20 \cdot 20$

Table 1: The applied controller equations and the used parameters

Identifier	Description
φ_{ps}	Desired orientation around the axis orthogonal to the current course. Positive φ_{ps} leads to positive translational acceleration parallel to the course.
φ_{qs}	Desired orientation around the axis parallel to the current course. Positive φ_{qs} leads to positive translational acceleration orthogonal to the course.
P_x	Cyclic pitch for movement around the helicopter's x-axis
P_y	Cyclic pitch for movement around the helicopter's y-axis
P_c	Collective pitch of the main rotor
P_t	Tail rotor pitch
th	Throttle for the engine
v_x,v_y,v_z	Current velocity of the helicopter along the given axis of HCS
x,y,z	Current position of the helicopter in BCS
φ_x,φ_y,φ_z	Orientation of the helicopter around the given axis of HCS
ω_r	Current main rotor velocity
Δx	Distance to the destination point parallel to the current course
Δy	Orthogonal distance to the current course
z_s	Destination altitude in BCS
φ_{xs},φ_{ys},φ_{zs}	Desired orientation

Table 2: Description of used Symbols

Identifier	Value	Description
ω_{zs}	$10 \cdot 20 \cdot \frac{2\pi}{4096} \frac{rad}{s}$	Maximum angular velocity for changing heading
v_s	$3 \frac{m}{s}$	Maximum horizontal velocity
v_{vs}	$1.92 \frac{m}{s}$ (climb) $-0.96 \frac{m}{s}$ (decent)	Maximum vertical velocity
ω_{rs}	$1150 rpm \hat{=} 120 \frac{rad}{s}$	Desired main rotor velocity
$\varphi_{z_{max}}$	$100 \cdot \frac{2\pi}{4096} rad$	Maximum allowed deviation of heading for flight to next waypoint
φ_{xA}	$60 \cdot \frac{2\pi}{4096} rad$	Measured orientation for hovering
φ_{yA}	$0 rad$	Measured orientation for hovering
P_{cA}	1030	Measured collective pitch for hovering
P_{cG}	150	Collective pitch
P_{xG}	20	Cyclic pitch because of tail rotor
P_{yG}	10	Cyclic pitch because of slope
P_{tG}	440	Tail rotor pitch
th_G	125	Idle throttle
$d\omega_{rs}$	$40 \frac{rpm}{s} \hat{=} 4.2 \frac{rad}{s^2}$	Acceleration of rotor velocity before take off
z_E	$1.6 m$	Altitude for emergency climbing
P_{cE}	250	Offset for collective pitch for emergency climbing
t_E	$\frac{40}{20} s$	Suspension of reactivating of emergency climbing
t_{ET}	$\frac{160}{20} s$	Suspension of emergency climbing after take off
P_{cT}	1250	Collective pitch for take off
v_L	$-0.48 \frac{m}{s}$	Vertical velocity for landing
z_L	$0.48 m$	Altitude for final landing phase “touchdown”
P_{cL}	$5 \cdot 20 \frac{1}{s}$	Decreasing collective pitch in final landing phase “touchdown”
t_{FS}	$\frac{100}{20} s$	Time for recovery after (semi) failsafe
k_{FS}	3	Increasing half life of controller for φ_{ps} and φ_{qs} during semi failsafe

Table 3: Controller parameters

4.4 Calculation of Desired Orientation

To get the desired helicopter orientation, which is used for controlling the cyclic pitch outputs, the previously calculated desired orientations φ_{ps} and φ_{qs} has to be transformed to φ_{xs} and φ_{ys}. This is done using the following equation. φ is defined in figure 5.

$$\begin{pmatrix} \varphi_{xs} \\ \varphi_{ys} \end{pmatrix} = \begin{pmatrix} -cos(\beta) & sin(\beta) \\ sin(\beta) & cos(\beta) \end{pmatrix} \cdot \begin{pmatrix} \varphi_{qs} \\ \varphi_{ps} \end{pmatrix} + \begin{pmatrix} \varphi_{xA} \\ \varphi_{yA} \end{pmatrix}$$

φ_{xA} and φ_{yA} are measured values in hovering state. They are added to separate built-in characteristics from influences such as wind. φ_{yA} can be set to zero, as it is very small. φ_{xA} is important because it is necessary to compensate the thrust of the tail rotor.

Due to this approach the controller is able to fly MARVIN with or without changing it's heading. The necessary orientations φ_{xs} and φ_{ys} for flying towards a given direction can be computed correctly, even if the heading is fixed to a user-defined direction. This can be done by setting the allowed angular velocity ω_{zs} to zero. Otherwise the helicopter first alters it's heading into the desired direction. The helicopter doesn't leave it's position until the deviation $\varphi_z - \varphi_{zs}$ is smaller than a given limit $\varphi_{z_{max}}$ (see table 3).

4.5 Mixers

As described in section 3.2, the output of one controller can be used to modify the output of another controller. According to table 1 this is done for P_c, P_t and th. According to equation 15, m has to be generated by applying a suitable transfer function to the values given in table 1 (φ_{xs}, φ_{ys}, th, P_c).

4.5.1 Collective Pitch P_c

P_c is influenced by φ_{xs} and φ_{ys}. Any deviation of the helicopters orientation from being upright means that more lift is required to maintain the same altitude. With controller output P_{cA}, which is suitable for hovering to keep MARVIN at the given altitude, this equation should be valid to maintain the lift in direction of z-axis of BCS constant (lift is proportional to collective pitch):

$$(P_{cA} + m_{P_c}) cos(\varphi_{xs}) cos(\varphi_{ys}) = P_{cA}$$

Solved for m_{P_c}:

$$m_{P_c} = P_{cA} \frac{1 - cos(\varphi_{xs}) cos(\varphi_{ys})}{cos(\varphi_{xs}) cos(\varphi_{ys})}$$

Since the angles φ_{xs} and φ_{ys} are always small, this dependency can be simplified. The main reason for simplification is the used microcontroller and it's limited abilities. This leads to the result:

$$m_{P_c} = \frac{P_{cA}}{2} (\varphi_{xs}^2 + \varphi_{ys}^2) = \frac{\varphi_{xs}^2 + \varphi_{ys}^2}{32} \frac{47}{1250}$$

4.5.2 Tail Rotor Pitch P_t

The tail rotor has to compensate the torque produced by the engine. Thus it is useful to take into account the output of the throttle controller to adjust the thrust of the tail rotor. We assume throttle to be proportional to the produced torque. Thus we can use a simple linear approach. The values are determined by experiments:

$$m_{P_t} = (th - 600)\frac{270 + 270}{100 - 1100}$$

4.5.3 Throttle th

The engine has to compensate the drag of the rotors. Most of the drag is produced by the main rotor and depends on the pitch. The values are determined by experiments:

$$m_{th} = \frac{P_c^2}{1024}\frac{500}{2200}$$

5 Special Maneuvers

Only controller algorithms for normal flight were discussed so far. They can be used for hovering as well as for flights to given waypoints. But there are several conditions, which require a special handling.

5.1 Emergency Climbing

During normal flight operations it is possible that the helicopter closes in on the ground or any other obstacle below. Since this is a dangerous situation, the helicopter has to evade such a situation immediately. As soon as the measured distance below the helicopter (using an ultra sonic range finder) falls below a given distance z_E, the collective pitch is increased to produce more lift. This is done by applying a predefined amount P_{cE}.

Since the mechanics can be damaged by rapid alterations of a controlled value (see table 1 for allowed steps), the controller increases the collective pitch according to the allowed rate. This is done by adjusting the operating point A, so that equations (9) and (10), respectively, produce the desired output. For case 1 the controller equation looks as follows (case 2 will produce the same result):

$$P_c = (v_z + A)f + m_{P_c}$$

After increasing collective pitch this equation should produce the new increased pitch using a different operating point A':

$$P_c + P_{cE} = (v_z + A')f + m_{P_c}$$

Combining these both equations leads to

$$A' = \frac{P_{cE}}{f} + A \tag{16}$$

The built-in limitations such as *min*, *max* and *step* (see table 1) are applied afterwards, so that the collective pitch is increased accordingly. The changed operating point ensures that the offset P_{cE} will be continued next time step. Of course the operating point is changed again in the future by the controller according to the real operating point. This behavior is obviously desired. But the effect of the temporary offset is sufficient to avoid the collision with the ground.

Since the acceleration of the helicopter is not sufficient to leave the dangerous area within one time step, this mechanism of emergency climbing would be activated multiple times, which is not desired. To avoid this, a reactivation is suspended for a given delay t_E.

5.2 Take Off

On the ground there are several values defined as parameters. This is necessary to stabilize the helicopter on the ground. It is not possible to measure all influences like thrust of the tail rotor because the helicopter is more or less fixed to the ground due to friction. But nevertheless these forces are applied to the helicopter and they are important at least during take off. Table 3 shows all predefined values for the ground (P_{cG}, P_{xG}, P_{yG}, P_{tG}, th_G).

First of all, the rotor has to reach the given velocity ω_{rs}. As the used PID controller would course a very strong acceleration, which could damage the helicopter, the desired velocity is increased slowly from zero to ω_{rs} at an acceleration of $d\omega_{rs}$. Once the desired velocity is reached, the helicopter is ready for take off.

Taking off is more dangerous than normal flight, because at the beginning the ground is very close. There is no tolerance zone for correcting controlling mistakes. At the very beginning there is an additional difficulty: While the helicopter is in contact with the ground, the helicopter acts in a different way to controller commands. It cannot change its orientation, for example. But if the controller notices that the helicopter does not follow the given commands, the controller outputs will be increased for compensation. Once the helicopter leaves the ground, this can lead to dangerous movements, as now the helicopter can easily alter its orientation.

To overcome this, MARVIN leaves the ground very quickly without controlling much. Just the collective pitch is increased, so that the helicopter can leave the ground at a large acceleration to reach a secure altitude as quick as possible. According to equation (16) in section 5.1 the new value is set by adjusting the operating point accordingly:

$$A' = \frac{P_{cT} - P_{cG}}{f} + A$$

As the operating point is changed automatically in future time steps to meet the real operating point of the helicopter, the given value P_{cT} is never reached. Nevertheless P_{cT} defines the climbing speed for take off.

Finally the mechanism of emergency climbing has to be deactivated until the helicopter has reached an altitude above z_E. Otherwise this mechanism would interfere with taking off. This is done similar to the described prevention from multiple activation of emergency climbing in section 5.1. The (re)activation of emergency climbing is suspended for a given period of time t_{ET}.

5.3 Landing

The difficulties mentioned for take off can be applied here, too. The closeness to the ground is dangerous. And again the controller should not try to control the orientation, when the helicopter already has contact to the ground, because this could lead to incorrect operating points and thus dangerous torques. This means it is necessary to land without controlling the same way as for normal flights.

At the beginning of landing the helicopter descents normally. Just the velocity is reduced to v_L. When the measured altitude above ground falls below z_L, this normal decent is finished and the final landing phase called "touchdown" is reached.

In this phase the helicopter decreases collective pitch at a given speed of P_{cL} until P_c reaches the predefined value of P_{cG}. At this point the landing is finished and the controller switches to the defined ground values, explained in section 5.2.

5.4 Failsafe

Many of the controller equations depend on knowledge about the current position of the helicopter. This is measured mainly by a differential GPS system. Since reception of the necessary satellite signals can be disturbed, accuracy of the resulting position can be affected.

During normal operation the reached precision of received position is $\pm 1cm$. If there are problems this can change to $1m$. Since the output of the GPS system contains this information, the controller can change its behavior in such a case. The controller switches to a special case called *semi failsafe*, which still allows flying, since there is valid GPS data.

If there is a fatal error condition, which means that there is no valid information from the GPS system, there is another slightly different case called *failsafe*.

To prevent repeatedly switching between (semi) failsafe and normal operating if GPS quality changes several times in a short period, the controller remains in semi failsafe at least for a given time t_{FS} (see figure 6).

As an accurate position is needed for movements close to obstacles, any dangerous operations should be aborted if possible. This includes take off and landing. Take off is suspended until semi failsafe is over. Landing is aborted if the controller enters (semi) failsafe.

At semi failsafe small alterations of position deviations cannot be recognized precisely. The controller has to wait for larger deviations, i.e. controlling more slowly. This can be done by increasing the half life of the controller for desired orientation φ_{ps} and φ_{qs}:

$$k' = k_{FS} \cdot k$$

Due to this single modification the helicopter is able to fly even with imprecise GPS data. But since the controller can not compensate external influences such as wind as

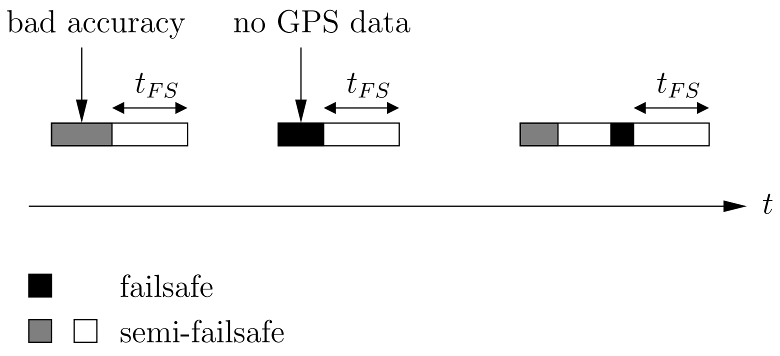

Figure 6: Correspondence of GPS problems and (semi) failsafe

fast as during normal flight, the flying behavior is very sensitive. This means, semi failsafe is not a good choice for normal flying. It is just an attempt to deal with short GPS problems.

Without any information of the current position at failsafe it is not possible to control the position of the helicopter. This is just an emergency state to keep the helicopter in the air until the GPS works again. At present the desired orientation φ_{ps} and φ_{qs} are not changed any more after switching to failsafe. For hovering this means the helicopter will remain hovering. In any other situation this means, the helicopter will leave its position. To keep the altitude, which cannot be measured either, additionally collective pitch P_c is kept constant. Since the orientation can still be measured without GPS, it is possible to keep the orientation at the given values φ_{ps} and φ_{qs}.

If the failsafe lasts very long, the helicopter will have left its position horizontally more or less. The covered distance depends on the values of the fixed orientation. The altitude can have changed, too. If the helicopter descends due to the fixed pitch, the ultra sonic range finder below will cause emergency climbing (section 5.1) if necessary. As long as there is no obstacle and the fixed values are not too bad, the helicopter can survive a temporarily breakdown of the GPS.