FIGHTER AIRCRAFT OFFLINE SIMULATION IN TERMINAL FLIGHT PHASES UNDER UTILIZATION OF PILOT MODELLING

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Abstract

In order to assure safe operations of an aircraft, it is important to focus the clearance activities not only on manoeuvring during the mission segment but to cover the terminal flight phases, i.e. take-off and landing, as well. Especially the transition from air to ground can be a challenging task for the pilot e.g. if strong crosswinds act on the aircraft. This is why clearance activities usually incorporate manned landing simulations under most adverse conditions. Manned simulation obviously can only take place in real-time, has a notable overhead for preparation, and the availability of slots for such sessions is rather limited. Hence, having a good understanding of the question, which configurations or conditions are most critical, is decisive.

The to be presented work contributes to that understanding by paving the way for a more extensive pre-assessment of configurations and conditions based on offline simulation ahead of manned simulation via the implementation of an automatic landing controller utilizing pilot modelling. Controller design and testing take place in MATLAB/Simulink with a modular hybrid 6-DoF aircraft simulation capable of representing in-service aircraft, generic benchmark aircraft, and future concepts. Recordings from actual manned simulation support the process of tuning the pilot model and provide first qualitative indications towards a future validation of the overall approach by comparison of landings in manned and offline simulation.

1. INTRODUCTION

In order to assure safe operations of an aircraft, it is important to focus the clearance activities not only on manoeuvring during the mission segment but to cover the terminal flight phases, i.e. take-off and landing, as well. Especially the transition from air to ground can be a challenging task for the pilot e.g. if strong crosswinds act on the aircraft. This is why clearance activities usually incorporate manned landing simulations under most adverse conditions. Manned simulation obviously can only take place in real-time, has a notable overhead for preparation, and the availability of slots for such sessions is rather limited. Hence, having a good understanding of the question, which configurations or conditions are most critical, is decisive.

The to be presented work contributes to that understanding by paving the way for a more extensive pre-assessment of configurations and conditions based on offline simulation ahead of manned simulation via the implementation of an automatic landing controller utilizing pilot modelling. Controller design and testing take place in MATLAB/Simulink with the Flight Dynamics department's modular hybrid 6-DoF aircraft simulation capable of representing in-service aircraft, generic benchmark aircraft, and future concepts. The aircraft model applied for the underlying work is for confidentiality reasons a generic one and shall be introduced in Section 2. Focussing on the flight phase of landing, Section 3 shall introduce the applied controller. Based on the research interest of one of the authors, it was pre-defined to investigate Model Predictive Control without comparison to competing control approaches for this work. The landing controller at that stage is independent of pilot modelling aspects, which shall be covered in Section 4. The focus thereby is on the Hosman Descriptive Model, which got selected for application in the context of this work after a pre-assessment of different pilot models based on control theory, human physiology, and intelligence techniques. For the sake of simplicity, the pilot modelling task shall initially be discussed independent of the MPC landing controller from Section 3 and it is only Section 5 that shall combine and assess both aspects before Section 6 provides the authors' conclusion together with an outlook to future work.

2. AIRCRAFT MODEL

This section introduces the aircraft model applied for the underlying work. In order to be representative for other platforms in the focus of the Flight Dynamics department in Manching, it should be of a highly agile fighter aircraft, but at the same time it must remain generic in order to allow for its application for academic purposes. Re-use of an already existing MATLAB/Simulink framework of the department for modular hybrid 6-DoF aircraft simulation was not only possible but even encouraged, but unclassified data for the parametrisation of the benchmark aircraft model had to be sourced externally. As previously described e.g. in [1, 2, 3] (sorted by increasing detail), the Aero-Data Model in a Research Environment (ADMIRE) [4, 5, 6] of the FOI, i.e. the Swedish Defence Research Agency, ideally served the purpose of providing the required mass-CG-inertia properties, the aerodynamics and the engine, actuator, and sensor dynamics. For work like the underlying, where the focus is not on the primary control laws, it is even possible to adopt the FOI's MATLAB/Simulink FCS implementation.

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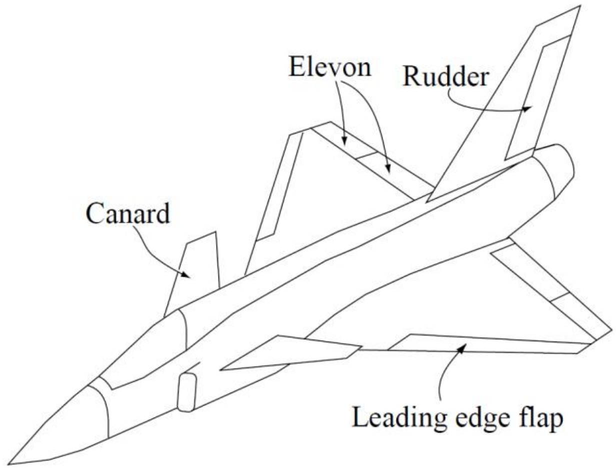

FIG 1. Aircraft configuration described by ADMIRE. [5]

Development of ADMIRE started in 1997 and the present work builds upon data of release 4.1 from 2006. As shown in FIG 1, the ADMIRE describes a delta-canard aircraft with one engine, representing a light generic fighter. Its nominal configuration data are listed in TAB 1 for easy reference. All of its control surfaces, i.e. the leading edge flaps, canards, elevons, and rudder, as well as the engine are commanded via the FCS based on the pilot's inputs through stick, pedals, and throttle, as well as the flight state. Longitudinal stick inputs represent a pitch rate command in the relevant flight envelope while lateral stick inputs are interpreted by the FCS as roll rate commands. Deviating from that logic, a pedal input does not represent a yaw rate command but is directly mapped to a sideslip command. The underlying primary control laws are scheduled over Mach number and altitude down to M0.22 in 66 ft. At lower values, FOI's original FCS applies linear extrapolation for the scheduling, but this proved according to [2] inacceptable for the terminal flight phases, especially w.r.t. rudder commands. Hence, extrapolation is disabled for the FCS in the context of this work and the gain design of M0.22 is kept for lower speeds.

Parameter	Value	Unit
Wing area	45	m²
Wing span	10	m
Wing chord (mean)	5.2	m
Mass	9100	kg
I_x	21000	kg m²
I_y	81000	kg m²
I_z	101000	kg m²
I_{xz}	2500	kg m²

TAB 1. Nominal configuration data. [4]

Utilising i.a. the atmosphere model of the Flight Dynamics department's simulation framework, the external forces and moments acting on the aircraft are determined based on the aerodynamics and engine data provided by the FOI. They drive the state propagation according to the integration flow of rigid-body equations of motion (EoM) shown in FIG 2, which also requires the aircraft's weight and balance data and which is implemented in Simulink as the very core of the existing modular hybrid 6-DoF aircraft simulation.

One noteworthy shortcoming of the model at hand is its lack of a representation of the aerodynamic ground effect. There is neither a dedicated implementation for the ADMIRE nor does the Flight Dynamics department's MATLAB/Simulink framework provide a generic approximation for delta-wing configurations yet. In most contexts, this is omissible, but as shown by [7] for an aircraft with similar wing geometry, it has to be expected that the ADMIRE would experience a significant gain in lift and pitch-up moment before touch-down due to the ground effect and thus flare automatically without pilot inputs. For the work at hand, this means that the assessed landing manoeuvre needs to deviate from the typical landing procedures of a delta-canard aircraft in order to prevent unrealistically high sink rates. As to be discussed further in Section 3, the landing controller will hence actively apply pitch stick inputs before touchdown to perform a flare despite the absence of a ground effect.

For several aspects of this work, there is the need for linear representations of the aircraft's dynamics. Such models are determined via numeric linearisation of the Simulink model in relevant operating points. A sufficient match of the linear and nonlinear dynamics for the purpose of this work got confirmed in the context of [1] and [2] by the evaluation of system responses for step inputs at their respective limits or command doublets of realistic magnitude, respectively.

Due to the modularity of the Flight Dynamics department's MATLAB/Simulink framework, it will be easy to replace just the FCS or the whole airframe parametrisation in case the conducted work shall be transferred to a different set of primary control laws or even a completely different aircraft.

3. LANDING CONTROLLER

As presented in detail in [1], a landing controller based on Model Predictive Control (MPC) has been developed exemplarily for the fighter aircraft model introduced in Section 2. This section elaborates on the fundamentals of that controller as well as its design and assessment.

The general intent for the landing controller is to supply the FCS with stick, pedal, and throttle inputs that result in flying as good as possible along a reference trajectory that would be in the mind of a pilot adhering to typical procedures for approach and landing. These inputs shall be representative for the applicable piloting techniques, e.g. by controlling the glide path angle via longitudinal stick inputs, but there is no intent to cover the human pilot's actual dynamics with the landing controller. Modelling of the pilot shall be addressed independently in Section 4.

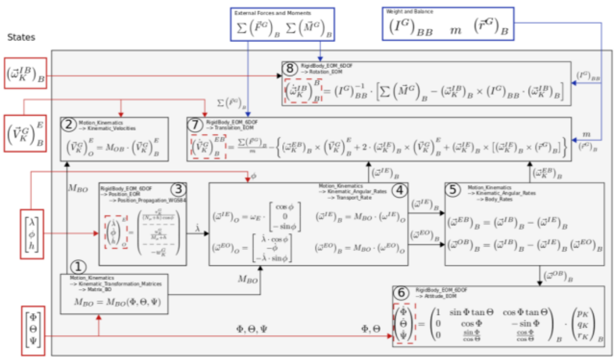

FIG 2. Integration flow of rigid-body EoM. [3]

3.1. Fundamentals

Since defining the outer loop of the landing controller, the procedures applied for approach and landing in the context of this work are briefly described in this sub-section on the fundamentals of the landing controller. The procedures are then used to derive a reference flight path for the landing controller together with the applicable piloting techniques or control strategies that have to be reflected by the outer loop, which is motivated thereafter. A (very) basic introduction to Model Predictive Control shall conclude the fundamentals.

3.1.1. Approach and Landing

Landing is regarded as one of the most challenging manoeuvres that an aircraft routinely performs, requiring simultaneous and precise control of multiple aircraft states. After lowering the landing gear, the throttle input shall be reduced to arrive on a -3° final with the recommended angle of attack (AoA). Controlling the AoA is there preferred over controlling the speed as it is more robust w.r.t. configuration variants. The recommended AoA on final is basically fixed for a wide range of aircraft masses while the corresponding trim speed varies significantly. Should the aircraft be below the desired flight path, it can maintain level flight until the final is intercepted. Typically, no flare is required for a delta-canard aircraft since it flares by itself due to the ground effect (see discussion in Section 2). For simulations without according modelling, however, longitudinal stick inputs (back) shall be increased approximately 50 ft above ground to gradually reduce the descent rate and bring the flight path angle near zero, ensuring in line with [8] a smooth touchdown and minimizing the impact on the landing gear. Mathematically, the required flare can be described through an exponential function that should be shifted towards the ground for less dispersion of the actual touchdown point. As shown in FIG 3, it should additionally be considered that the aircraft's centre of gravity and the main wheels are offset in the geodetic z-direction as a function of the pitch attitude. At main wheel touchdown, the throttle has to be reduced to the idle position. In case of crosswind, the final shall be flown with the aircraft ground track aligned with the runway and the pilot shall compensate for the crosswind using the crabbed approach technique. Prior to landing, the fuselage shall be aligned with the runway by gradually increasing the pedal input until touchdown.

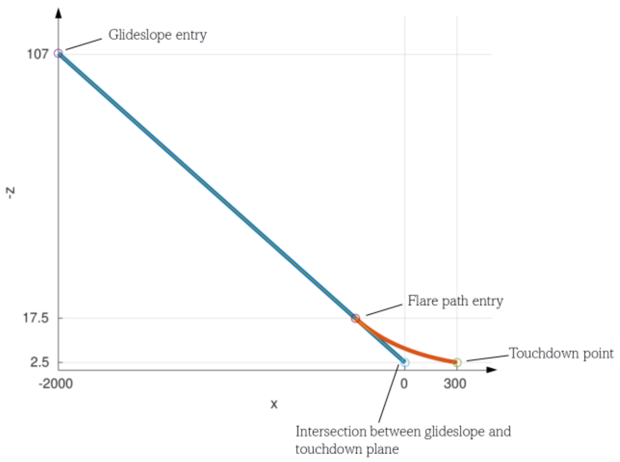

FIG 3. Side view of reference flight path (units: m). [1]

3.1.2. Outer Loop Control

The outer loop of the landing controller needs to reflect the human pilot's technique of converting lateral and vertical deviations from the reference flight path into relevant flight path angles and it has to provide appropriate targets for the angle of attack as well as the angle of sideslip. There are numerous approaches for the calculation of flight path angle targets (whereby [1] referred to [9] and [10]), and the aero-dynamic flow angle targets are basically constant and given via the recommended AoA on final, the resulting trim speed, and the acting wind.

3.1.3. Model Predictive Control

Model Predictive Control encompasses a set of optimal control techniques that utilize a process model to predict the future behaviour of the controlled system within a finite time interval, called the prediction horizon. By solving a potentially constrained optimization problem, MPC implicitly determines the control action over the designated control horizon. [11]

Every MPC problem depends on a reliable process model to predict the behaviour of the system with respect to future control input trajectories. The aim of the control system is to minimize the deviation between the reference trajectory and the predicted output trajectory (see FIG 4) within the specified prediction horizon. The time distance between the present and the starting point of the prediction horizon is selected such, that it is at least as long as the system's delay, since the current input variables to be calculated will only affect the control variable after this dead time. The prediction horizon should be long enough, so that the essential dynamics of the process model can be captured. The control horizon refers to the number of future time steps over which control actions are optimized. It determines how far into the future the control actions are explicitly computed within the optimization process. Its maximum appropriate length is the distance from the present up until the end of the prediction horizon, reduced by the systems delay. In order to quantify the deviation between the reference trajectory and the control variable, a scalar cost function is used. The calculation of the optimal control input results from the minimization of this cost function. The controller then implements the first value of the optimal control input in every time step and the value is calculated repeatedly for every new time step, with the window over which the cost function is formed being shifted by one sampling step. [12]

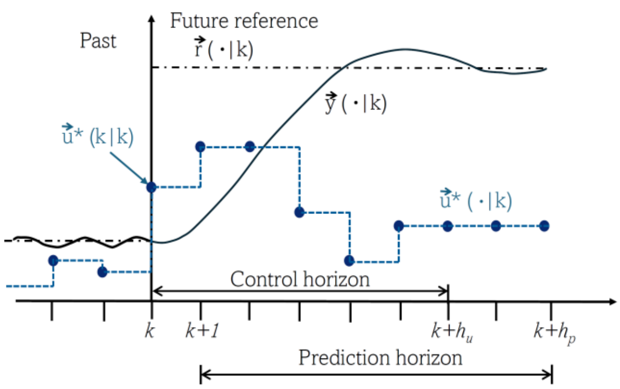

FIG 4. MPC working principle. [1]

Applying linear models and linear constraints for the MPC, as in the context of this work, the optimization problem becomes a quadratic program that is computationally efficient and solvable in real time for many applications as it is a convex optimization problem [13, 14]. Linear MPC, however, is limited to systems that can be adequately approximated by linear models. These models either have to have a wide validity range or they need to be updated regularly, which in turn increases the computational effort.

3.2. Controller Design

As depicted in FIG 5, the landing controller shall be placed in front of the existing FCS to supply it with stick, pedal, and throttle inputs. These inputs are crated in layers, starting on the outside with the generation of the reference flight path for approach and landing (see FIG 3), followed by the outer loop converting deviations from this flight path as well as the procedure-derived control strategies into commands for the MPC at the core of the landing controller. While [1] does elaborate on the design of all three layers, the underlying work will focus on the MPC as it is the outstanding element.

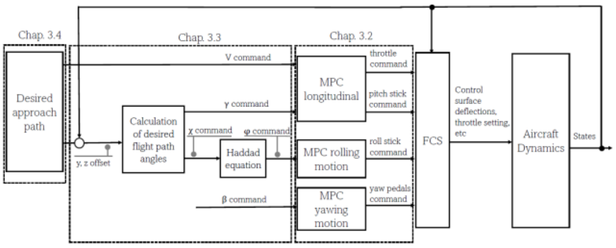

FIG 5. Model structure with MPC landing controller. [1]

As defined in [1], there shall be three independent MPCs. That is one multi-input-multi-output MPC for the longitudinal motion and a single-input-single-output MPC for the rolling and yawing motion, each. The longitudinal MIMO design does thereby deviate from the idealised piloting technique of controlling speed / AoA only via throttle and the glide path angle only via the pitch stick. This is an attempt of obtaining overall better results by providing the MPC with information on existing couplings. In order to be still representative for the technique of a fighter pilot, however, it must be assured via the longitudinal MPC's design that there is a preference for speed / AoA by throttle. To be precise, the controller for this work shall primarily apply throttle to follow a reference angle of attack (see Section 3.1.1 for the motivation). This is a deviation from the design presented in [1] but does not cause any systematic differences.

The actual design process for the three linear MPCs is quite straightforward since it was considered acceptable in the context of [1] and this work to utilise the proprietary Model Predictive Control Toolbox of MATLAB/Simulink. With this toolbox, it is sufficient to provide a linear representation of the plant as prediction model, together with settings for the prediction and control horizon as well as initial conditions, weights, and constraints where necessary.

With the typical manoeuvring expected during approach and landing, the nonlinear dynamics of the ADMIRE aircraft are approximated well by the corresponding linear models determined on the -3° final. This has been shown by [1] and it is hence sufficient to use a single prediction model per MPC and rely on a static landing controller per simulation.

The remaining parametrisation of the three MPCs was in part an iterative process with the assessment since aircraft specific guidance for the selection of control and prediction horizon or individual weights has not been available a priori. Constraining the manipulated variables, i.e. the stick, pedal, and throttle inputs, properly was on the other hand not an issue as per their physical limits.

3.3. Assessment

The obvious method for assessing the landing controller's performance is to run simulations with it in command. The assessment should thereby cover nominal conditions as well as challenging borderline cases. In the following, an approach aligned with the runway in level flight at 590 ft without wind shall represent nominal conditions (see FIG 6) and the corresponding approach with a crosswind resulting in a kinematic angle of sideslip of -7.5° (see FIG 7) shall exemplarily excite the rolling and yawing motion in a more challenging setup. Further examples for borderline cases, e.g. significant mass variations, other wind conditions, and offset landings, can be found in [1] (as well as [2]).

Direct assessment of the individual MPCs can as well be rewarding, especially during iterative controller design and assessment, as it allows for providing dedicated inputs to the MPC. Varying the magnitude of these inputs may further support confirming the validity range of the linear prediction models. There will be no respective assessment in this work but [1] dedicates a whole sub-section to the assessment of the tracking performance of the individual MPCs.

A thorough assessment of the landing controller naturally requires the definition of quantitative criteria for desired and adequate performance. The authors of [15] suggest such a definition in the context of handling qualities assessment of a business jet fly-by-wire flight control system. Despite the differences that may appear between the two aircraft types (business jet and delta-wing fighter aircraft) in dynamic scenarios, the fundamental principles of following a stable approach path, maintaining an approach speed, and ensuring a precise touchdown during the approach and landing phases can be assumed to be common since the dynamic characteristics of the aircraft are not of primary importance. This is why [1] applies the performance criteria of [15] for the overall landing controller assessment. It must however be acknowledged that the outer loop controller has a significant impact on the quantitative criteria without being in the focus of this work. Hence, there shall only be a qualitative assessment of the landing controller (as well as the pilot model and a combination of both later on) in this work.

Starting with the nominal case, FIG 6 presents an excellent tracking of the commanded AoA until the flare is initiated, but there is basically no weight on the AoA tracking for that final phase in longitudinal MPC. Significant changes of the throttle input are limited to the initial change in glide path, which adds energy to the system, and the discontinuous switching between the gross and fine tracking modes of the outer loop controller at approx. 30 s. The commanded glide path is quickly established and properly tracked even during the flare. Based on the rather small magnitude of the pitch stick inputs sufficient for the flare (without a ground effect), it is fair to say that the exponential function of the reference flight path should be updated in the future for a more aggressive and then slightly delayed flare.

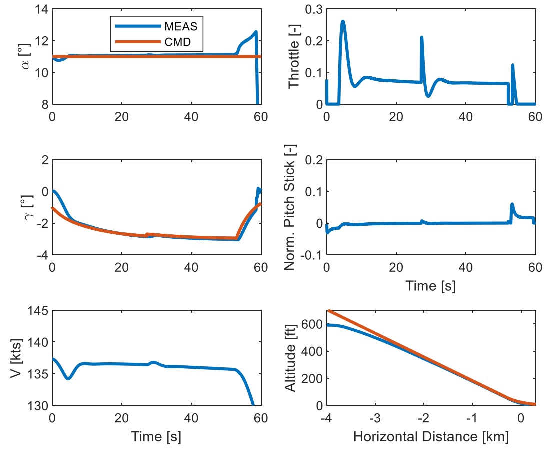

FIG 6. Approach without wind controlled by MPC.

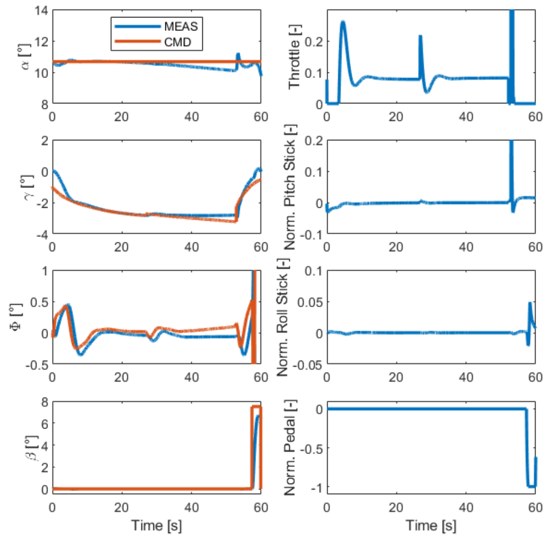

FIG 7. Approach with crosswind controlled by MPC.

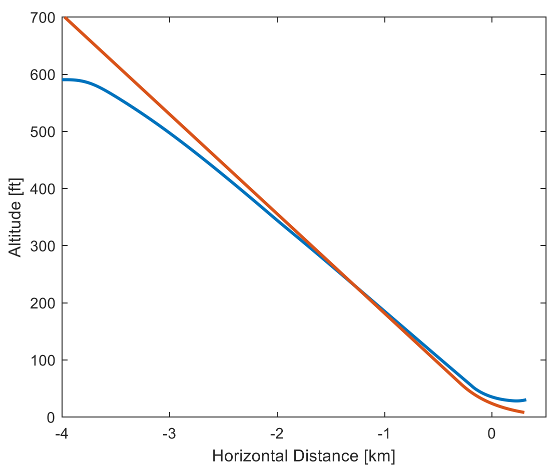

FIG 8. Trajectory with crosswind if controlled by MPC.

Compared to the nominal case, there is a clear degradation of the AoA tracking performance with crosswind for similar throttle inputs (see FIG 7). Differences in airspeed between both cases should not contribute significantly to that effect since the design model as well as the initial conditions have been updated accordingly for the crosswind MPC. As the angle of attack deviates more and more from the command, there is also a notable error in the glide path angle, but since the MPC mainly relies on its internal model of the plant, there is no timely compensation of that error. This results in a trajectory above the reference flight path and due to the too shallow glide path at flare initiation, there is not even a proper touchdown at the end of simulation (see FIG 8). The initial small variation in bank angle results from inputs of the outer loop controller based on a pure altitude error in the presence of a kinematic angle of sideslip. While the AoA is close to its initial condition, there is proper tracking of the bank angle command. As the angle of attack deviates more and more from the initial condition, which is the only value known to the rolling motion MPC, also the bank angle error increases but stays rather small. Finally, the de-crab to align the fuselage with the runway is performed smoothly but the aerodynamic angle of sideslip does not reach the required 7.5° at the end of simulation.

Overall, the presented controller provides a relevant landing trajectory with the caveat that a human pilot would not apply aggressive throttle spikes like those of FIG 7 and FIG 8. What is more, unlike the MPC, a human pilot would never ignore an observable error and thus operate even in the presence of crosswind closer to the commanded values. Shortcomings of the outer loop must not be attributed to the MPC but need to be fixed in the future to allow for a thorough assessment against the quantitative performance criteria on the way to an updated MPC landing controller design that is fit for validation.

4. PILOT MODEL

As presented in detail in the context of [2], a pilot model based on the Hosman Descriptive Model [16, 17] has been developed exemplarily for the fighter aircraft model introduced in Section 2. This section elaborates on the fundamentals of pilot models in general and the selected one specifically as well as its tuning and assessment.

The general intent for the pilot model is to shape the stick, pedal, and throttle inputs to the FCS such that they become representative w.r.t. the human pilot's actual dynamics.

4.1. Fundamentals

In order to be able to properly follow the subsequent discussion of pilot modelling, it is important to understand pilot characteristics, such as how pilots control an aircraft, as these are the necessary foundation for modelling the human operator. Some input w.r.t the piloting techniques during approach and landing has already been provided in Section 3.1.1 and this sub-section on the fundamentals of pilot modelling adds some more general aspects. A (very) basic introduction to the Hosman Descriptive Model shall conclude the fundamentals. The interested reader has to be referred to [2] and the quoted primary references for further details due to limited space in this work.

4.1.1. General Aspects

During their introduction, one of the applications of pilot models was the early estimation of the Handling Qualities. While this does not pose one of the main points in the context of this work, it can be used to understand where the pilot influences the system. A good overview for that aspect is e.g. provided by [18].

Another important aspect is the fact that every pilot has his own characteristics depending on the outside variables, which can vary heavily. McRuer [19] divided these influences into four main categories, i.e.

- task variables,
- environmental variables,
- procedural variables, and
- pilot-cantered variables.

A third and vital aspect for implementing pilot models is the human physiology. First, the neuromuscular system, which describes the process of how a command in the operator’s mind is converted into the consequential action, has to be understood. Again, valuable input comes from McRuer [20]. Next, the different sensor pathways available for the pilot to receive information about the aircraft’s state are relevant. Details on the visual system, the vestibular system, and the proprioceptive system are provided by [21]. And finally, it is necessary to bring all facets of human physiology together, which is attempt via the Isomorphic Structural Model [20] represented in the block diagram of FIG 9.

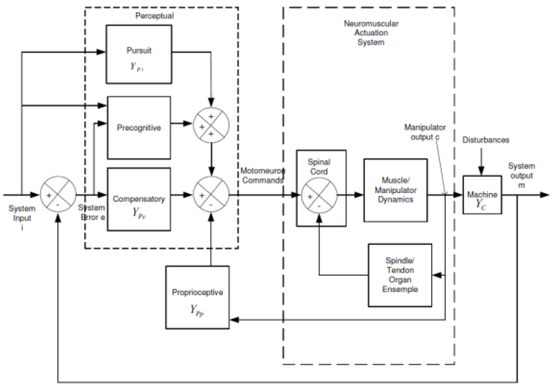

FIG 9. Block diagram of Isomorphic Structural Model. [22]

The Isomorphic Structural Model is not utilised as a pilot model, as many parameters are unknown and hard to determine. However, the model provides a good overview of the structure of the human operator while providing the basis for so-called physiology models that try to model the human physique as realistic as possible. The Hosman Descriptive Model to be introduced next is such a model.

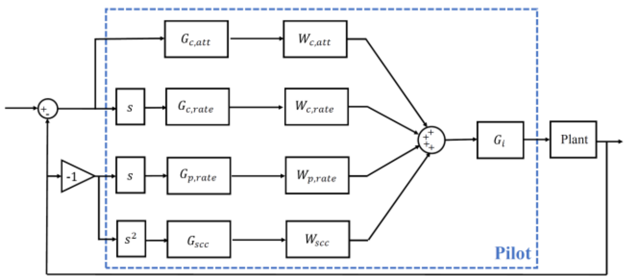

FIG 10. Block diagram of Hosman Descriptive Model. [2]

4.1.2. Hosman Descriptive Model

The Hosman Descriptive Model belongs to the class of physiology models and originated during the 1990s [16, 17] because of the rise of fly-by-wire systems, which led to the need for a better depiction of visual and vestibular systems. Briefly summarised, the Hosman Descriptive Model treats the human as a single-information processor with multiple inputs from the different sensory systems (see FIG 10).

Among these sensory inputs are the central vision fed by the attitude error as well as its rate of change, the peripheral vision reacting on the rate of change of the attitude state (independent of the command), and the vestibular system responding to the perceived acceleration state. All three pathways of vision shall thereby be represented through simple delays of specific value while the vestibular system shall be described by over-damped 2nd order dynamics. For each sensory input, there is a weighting factor accounting for the importance of the respective sensory pathway to the human operator. The combined information is then feeding the central nervous system and is processed as a single information. That final part shall be represented by a central gain with additional delay for the information transport via the central nervous system. As suggested by Hosman as a possible extension of his original model, the neuromuscular system shall be considered (deviating from FIG 10) via dedicated 2nd order dynamics (with a typical damping of 0.7 and a natural frequency in the region of 10 rad/s) after the single-information processor.

4.2. Model Tuning

With a structure at hand, it is next required to tune the pilot model for the to be performed task, which is not necessarily a single one per flight phase. During approach and landing, the pilot has to arrive on the reference flight path in a target following task by gross manoeuvring and will then switch to a disturbance rejection task with fine tracking inputs once established.

When initiating this work and [2], a theory to be checked was, that available recordings of landings under different conditions from manned simulation of a comparable aircraft configuration can be applied for tuning of pilot models for the target following task and the disturbance rejection task alike. However, before consulting these data that were not created with the task of pilot modelling in mind, a dedicated single-axis experiment should be conducted and recorded to create a foundation for the first attempts of model tuning. The setup and all results of the single-axis experiment are presented in [2], but in the context of this work, it is only important that this pre-assessment motivated the selection of the Hosman Descriptive Model and that it served as a proof of concept for the model tuning via optimization with a Genetic Algorithm [23] as an alternative to merely relying on parameters from literature.

4.2.1. Target Following Task

For the target following task, it became quickly obvious that the available recordings from manned simulation were not rich enough in terms of energy brought into the system at relevant frequencies to allow a proper system identification of the pilot. What is more, due to limited meta-information it was not even always possible to extract the applied targets.

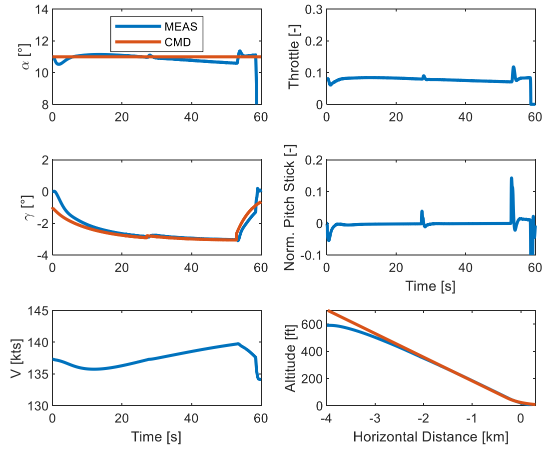

FIG 11. Approach controlled by pilot model without wind.

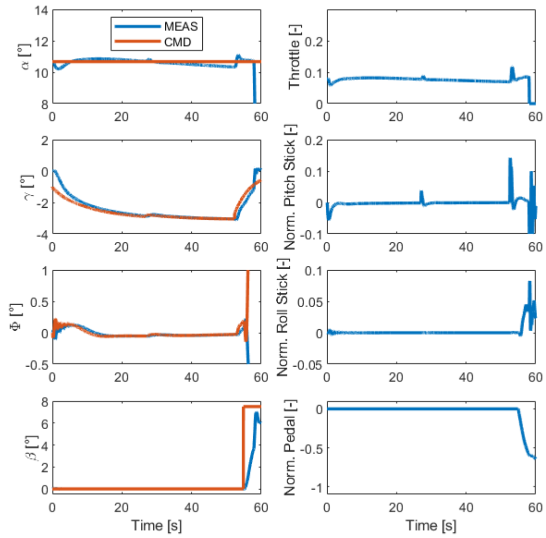

FIG 12. Approach controlled by pilot model with wind.

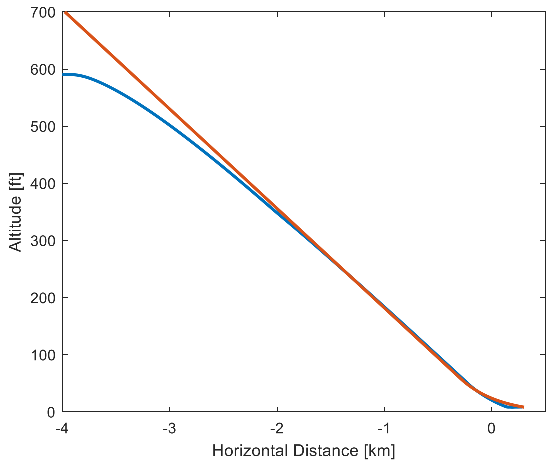

FIG 13. Trajectory if controlled by pilot model with wind.

An observed stick input might be in consequence of a new target value, but the pilot might as well just have kept the aircraft arbitrarily aloft while discussing the setup of the next test point of the simulator session with the tasking engineer.

The target following model shall thus rely on the assumption of the creators of the Optimal Control Model, that the pilot acts optimal within his possibilities [24]. That means, the parametrisation of the Hosman Descriptive Model is said to be valid once the tracking performance bounded by the human characteristics represented through the pilot model cannot be optimized any further by the Genetic Algorithm.

4.2.2. Disturbance Rejection Task

For the disturbance rejection task, on the other hand, it is possible to estimate the applicable targets from the existing recordings when focusing on the fine tracking segments and applying a few assumptions based on the procedures. With the targets at hand, a system identification of the pilot can be performed next. The obtained information is finally used to find the parameters for the disturbance rejection task. The pilot model and the system identification are aligned by minimising a cost function based on frequency responses of the systems.

The initial parametrisation is obtained from [16] and only the processing gain is modified to minimise the cost function. Changing the weights is not considered as the disturbance rejection of a normal distribution is assumed to be a task similar to the one originally explored by Hosman.

4.3. Assessment

Independent development of the aspects landing controller and pilot model in [1] and [2], respectively, lead to slightly different implementations of the outer loop that feeds the MPC or the pilot model based on the deviation from the reference flight path. For a performance comparison of both variants, it is hence reasonable to connect the pilot model for its subsequent assessment to the outer loop of [1] that has already been discussed in Section 3. Due to a similar input and output structure of the MPC and the pilot model, this is an easy task in MATLAB/Simulink.

Relying already on the outer loop controller of Section 3, it is only rational to assess its aligned approach without wind and its corresponding crosswind approach in the following.

Starting with the nominal case, FIG 11 presents reasonable tracking of the commanded AoA with only smooth changes of the throttle input. The commanded glide path is quickly established and properly tracked even during the flare.

Compared to the nominal case, there is no degradation of the AoA or glide path tracking with crosswind (see FIG 12) and the actual touchdown is only slightly offset from the reference flight path (see FIG 13). The initial small variation in bank angle results from inputs of the outer loop controller based on a pure altitude error in the presence of a kinematic angle of sideslip. The overall bank angle tracking is thereby excellent and only the small initial oscillations, hinting at a too high weight in the according target following pilot model, are objectionable. Merely the de-crab is not fully convincing with a slower build-up of the required angle of sideslip.

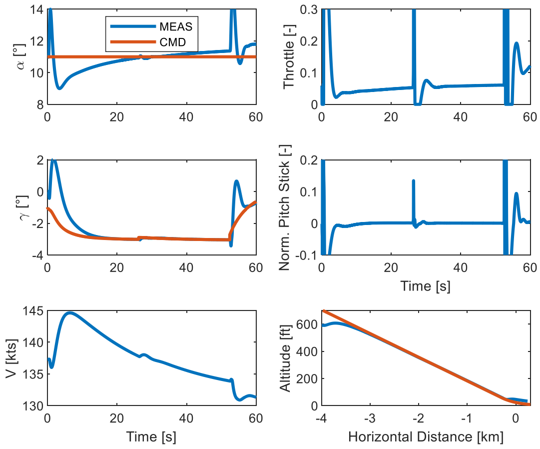

FIG 14. Approach controlled by MPC plus pilot model.

Overall, the presented pilot model provides in combination with the outer loop controller a relevant landing trajectory. Like a human pilot, the pilot model attempts to compensate for observable errors. Shortcomings of the outer loop must not be attributed to the pilot model but need to be fixed in the future to allow for a thorough assessment against the quantitative performance criteria of [15] during rather limited updates of the pilot model. For validation of the pilot model, there is a further demand for dedicated manned simulations as the approach and landing performance criteria do not target all relevant features of a human pilot's dynamics.

5. COMBINATION

This section discusses the combination of the developed landing controller and pilot model, that is ultimately required on the way towards a more extensive pre-assessment of landings via offline simulations in the clearance process.

While the similar input and output structure of the MPC and the pilot model were beneficial for the previous assessment, it becomes an issue when attempting to combine them. Both elements use α, γ, Φ, and β commands to generate throttle, stick, and pedal inputs, which means that it is not directly possible to connect them in series.

An easy way for the combination would be a parallel setup since both elements have already been used independent of each other. That way, reasonable results might be obtainable (if the system does not immediately depart from pilot model induced oscillations), but the resulting setup would not qualify as an actual representation of a human pilot performing a manual landing. It would rather describe a human pilot correcting for imperfections of an automatic landing system that does not consider the parallel inputs.

The approach that has to be pursued instead to obtain an actual "model predictive pilot" is a re-parametrisation of the MPC. If the controller provides a modified version of its own angle command inputs as outputs, then these can feed the pilot model set in series. That re-parametrisation requires to consider the pilot model also for the linear reference dynamics, and constraints applicable to the MPC's manipulated variables, previously given by the command range of the pilot inceptors and typical limits for their application, need to be revised.

An early prototype implementation of these updates confirms that the overall idea of a "model predictive pilot" is viable but the obtained results (see FIG 14) are not yet representative for a human pilot. The tracking performance is even without wind worse than for the individual elements assessed in Sections 3 and 4 and the stick and throttle input characteristics are too aggressive for the given flight phase. However, more adequate constraints applied to the MPC might resolve these issues in the context of future work.

6. CONCLUSION & OUTLOOK

In the context of this work, a landing controller utilising Model Predictive Control as well as a pilot model based on the Hosman Descriptive Model have been developed and assessed. Further, the possibility to connect both elements in order to provide (in the future) an excellent representation of the human pilot in terminal flight phases was discussed.

During the assessment, various shortcomings of the outer loop controller have been identified that need to be resolved before further work on the MPC and pilot model as they prevent a thorough quantitative evaluation of the approach and landing performance. These limitations set aside; the following can be said:

Controlling the approach and landing trajectory via a static, i.e. time independent, MPC controller can already supply relevant simulation results with fixed wind if tuned for the nominal wind. This state is acceptable for pre-defined offline simulations if it is valid to assume that the pilot is provided with a correct wind forecast. With uncertainties, however, the landing controller would have to be expanded within the MPC theory, e.g. via adaptive elements, or by the introduction of additional feedback driven error controllers. Future work shall investigate these topics in comparison with completely different control strategies.
Controlling the approach and landing trajectory utilising only the pilot model (with the outer loop) provided comparable, if not better, results and the presence of uncertainties would not result in the need for structural changes. The tracking task is, however, only one part of the pilot model and there is a further demand for dedicated manned simulations for validation (and potential updates) of the pilot model.

Depending on the general progress with the MPC design, it will have to be decided whether further investigation of the combination of a landing controller based on MPC and the pilot model are worthwhile. The combination of a landing controller (of to be defined structure) and the pilot model, however, is still considered an important step towards more extensive pre-assessment of configurations and conditions via offline simulations ahead of manned simulation in the clearance process for the terminal flight phases and shall hence be pursued in any case in the context of future work.

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