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OPTIMAL GUIDANCE MODEL FOR GREEN TRAJECTORY GENERATION OF HELICOPTERS

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ABSTRACT

A guidance model for helicopters is developed which incorporates a non-linear mathematical model to simulate dynamic response of a helicopter, an optimization algorithm to determine optimal reference states in accordance with the objective functions, and a controller and SAS to trace the reference states generated by optimization. Developed model takes target/waypoint locations into account and generates an optimal trajectory throughout the flight simulation. Multiple target/waypoint conditions, obstacles as avoid regions and various objective functions are implemented to study flight path variations and improve the optimal guidance model.

INTRODUCTION

Considering the noise restrictions imposed on helicopter operators that confine flight paths conservatively as well as limit flight speed & altitude, a new methodology for developing noise minimal and green helicopter optimal flight trajectories have been studied under a PhD thesis at METU, Aerospace Engineering. The methodology incorporates performance, noise and fuel emissions to estimate optimal trajectory. Therefore the proposed methodology requires an optimal guidance model on top of which aeroacoustic and fuel consumption estimations will be developed. This paper presents the optimal guidance model development which takes helicopter instantaneous velocity and position into account, incorporates with target or waypoints that are desired to be reached and determines optimum path throughout the flight.

The optimality statement that this paper studies is the determination of the reference states of a helicopter by means of minimizing a cost function which incorporates the target waypoints to be reached, avoid regions in the flight domain and flight speed while employing helicopter and mission specific constraints. By selection of three body velocities and heading as the reference states to be determined by the optimizer and tracked by the controller, the problem is converted to a guidance problem solved as a trajectory optimization problem examples of which include genetic algorithms, pseudospectral methods, stochastic sampling methods and hill climbing algorithms [Bottasso 2008, Thomas 2010, Morris 2012 and Morris

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2013]. The choice of online optimization, lead to utilization of an approach similar to the latter of mentioned methods.

The optimal guidance model is basically composed of a helicopter mathematical model, an optimization algorithm to determine reference/desired states of the helicopter, a controller to trace the reference states, a SAS to stabilize the non-linear mathematical model which integrates the system in time to simulate total flight path. At desired frequency, optimization algorithm takes instantaneous helicopter states into account, determines optimal reference states which is then operated by the controller (a tracker) to generate helicopter control inputs to trace the reference states, the control inputs are then operated by the SAS and utilized by the mathematical model which integrates the state derivatives in time and feedbacks the states to the controller through the flight path. An optimal control approach, a LQR which is widely used to stabilize and control helicopter systems [Cour-Harbo 2009] is utilized for as SAS stage.

It is detected that a state feedforward is essential in the optimization loop, so that the estimated future behavior and consequences of current actions are included while generating the reference states [Dauer 2014]. By doing this, the stability problem around the target location and target states are eliminated.

Various cost functions, objective weights and constraints are utilized to study the path generation and tracking performances. The main contribution to the cost function is generated from the directional component that governs the path to the target or waypoint locations. A target or final state component contributes to the cost function with an increasing weight as the aircraft approaches to the target or waypoint location. Another contributor of the cost function is the power required component which concerns minimizing the fuel consumption throughout the mission. The obstacles in the flight domain are considered as avoid regions and employed as cost functions into the optimization algorithm. The contributions to the total cost function from the avoid regions are increasing with the decreasing distance to the obstacle center therefore acts like a potential function.

The improvements achieved with a state feedforward in the optimization loop, various cost functions including combination of achieving the goal (reaching the target location or waypoints), fuel consumption, achieving the final state (the state desired at the end of the path or target location) and keeping away from the single or multiple avoid regions are studied and results are presented with this paper.

METHOD

The methodology utilized in this study is combination of an optimization stage that generates the optimal path, a non-linear mathematical model that is utilized as the plant to represent the dynamic response of the system, a controller that tracks the generated optimal path and a SAS to stabilize the highly coupled and complex non-linear plant. While the plant, controller and SAS function in real time, a different operation frequency is employed for the optimization stage. At each optimization time step, a reference state vector representing the optimal path is generated by the optimization algorithm in accordance with the cost function and constraints. Then the reference state vector is utilized by the controller to generate the required control input set and the SAS stabilizes the plant. The reference states are kept constant until the next optimization stage. The architecture of the developed system is presented with **Figure 1**.

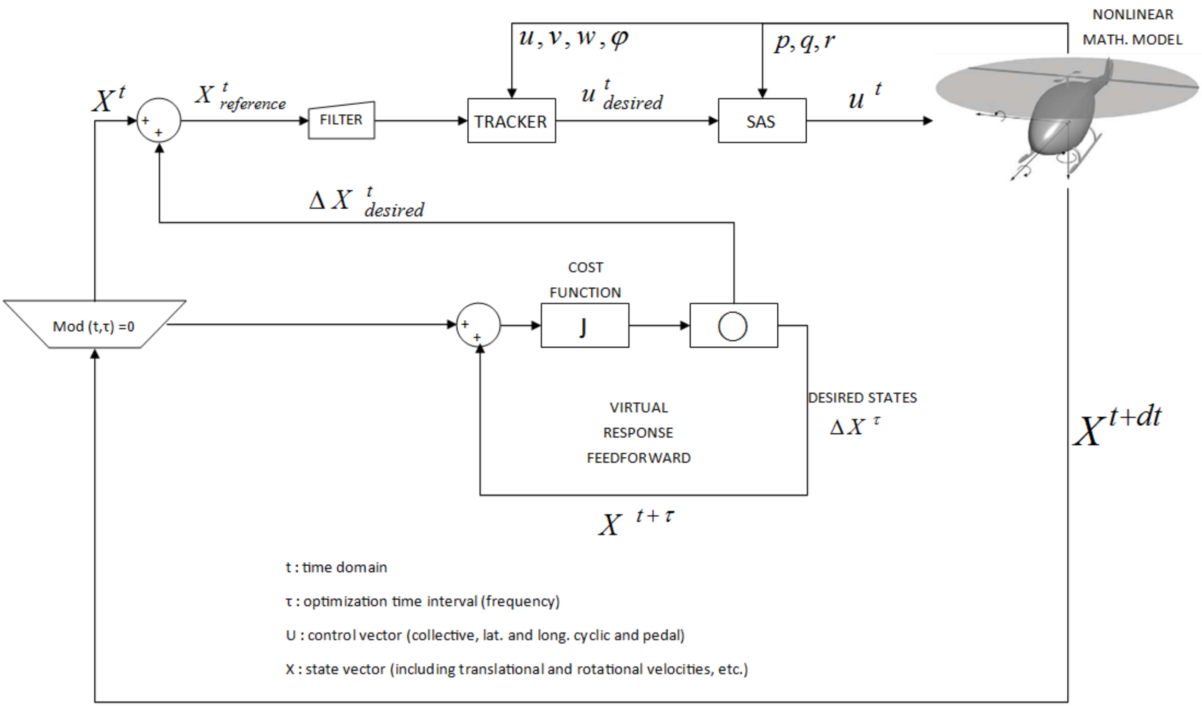

Figure 1 System architecture

The Plant – Mathematical Model

The mathematical model developed under the master thesis study at METU, Aerospace Engineering [Şenipek 2017], is utilized as base and improvements are performed to achieve the capability of interrupting the non-linear simulation at any instant, determining the optimal helicopter reference states utilizing the interrupted states and continuing the non-linear simulation from that instant. The mathematical model (GAVM) is a generic air vehicle modeling, design, analysis and simulation software uses object-oriented programming principles. GAVM includes several sub-components that exist in air vehicles such as propeller, rotor, wing and fuselage. The rotor and fuselage features are exploited in this study. The rotors are modeled based on blade element formulation which incorporates finite state dynamic wake model and inertial dynamics. Rotor model assumes rotor blades as rigid and a second order coupled flapping and lagging dynamics [Chen, 1987] are integrated with Pitt-Peters dynamic inflow [Pitt & Peters, 1981] and Peters-He finite state dynamic inflow [Peters & He, 1991] models. Rotor wake interference with wings and fuselage are modeled to take into account of the change in the effective angle of attack and dynamic pressure on the aerodynamic surfaces. Model for aerodynamic bodies includes table-lookup algorithm for aerodynamic force and moment calculations and can be used as a fuselage and any type of external aerodynamic component. The sub-components of an air vehicle are attached to a mainframe where 6-DoF dynamics is solved and flight dynamic state derivatives are calculated. Mainframe class holds the information about total forces and moments on C.G. and includes the routines for 6-DoF rigid body flight dynamics. There is a trim algorithm in GAVM which uses the classical unconstrained optimization of Newton's which searches for an equilibrium point for a defined flight condition by using the whole integrated dynamics and pilot controls. Therefore, any physically possible trim configuration can be analyzed by using the trimmer in the GAVM code. Moreover, total state space representation of an air vehicle around a point of equilibrium is obtained for simulation and control purposes. GAVM is compiled as a shared library and a console project to be used in different areas.

In this study, a dynamic linked library containing the mathematical model and required functions such as derivation, integration and storing purposes is generated. The mathematical model reserves a constant and protected sector in memory and time integration at each step is performed with an integration command that runs an integration routine present within the model library. All possible helicopter variables are studied to define the list of the states that are required to be stored so that the non-linear simulation can be continued without any perturbation. Whenever time integration is performed, all the model state and state derivatives are calculated and stored. This enables a quasi-unsteady integration scheme for which input and inputs derivatives for are already stored and ready to be utilized. It has been concluded that, variables including rotor dynamic and aerodynamic states such as multi body flapping angles & rates, inflow coefficients and 6-DoF airframe motion and accelerations are essential to be stored at each time whenever the optimization algorithm performs iterations on the related states. Then with re-loading the stored states into the mathematical model, the non-linear simulation is continues undisturbedly.

This also brings the ability to load the mathematical model library more than once with different initial conditions, trim conditions, flight conditions and configurations into the same computation domain and integrate separately advancing time domain. Consequently, simulation of multiple rotorcrafts in the same domain simultaneously is possible. Therefore, each aircraft in the domain has the position and velocity information of the other aircrafts. This information is utilized in the optimization algorithm whenever desired so that position and trajectory of the other aircrafts are considered during path generation. Inserting the contribution to optimization cost function and/or constraint list, the position and trajectory information of other aircrafts are utilized in avoidance of collision or entering into the avoid regions' of each individual aircraft. Exploration of this capability and its possible applications are left as future work of this study.

In this study, Westland Lynx helicopter is modeled. Lynx XZ170 has a 4-bladed main and tail rotor and has an empty weight of 2578 kg (5683lb), with a specified maximum takeoff weight of approximately 4535 kg (10,000lb). Flight tests examined a range of operating conditions corresponding to weights between 3880 kg to 5400 kg and speeds up to 158 knots. Validation study has been performed [Şenipek 2017] with experimental data of Lynx XZ170 helicopter [Lau 1993].

Optimization Stage

Trajectory optimization can be studied under two groups in terms of calculation type; offline and online approaches. The offline approach stands for optimizing and generating the trajectory before the flight, loading as a reference state into the specifically designed tracking controller which follows the desired trajectory throughout the flight. The online approach stands for optimizing the trajectory during the flight while considering instantaneous states and constraints, loading as reference, as updated and a specifically designed tracking controller follow the current desired trajectory. Higher fidelity, direct or implicit optimization methods are applicable for offline approaches as the computation is not expected to be performed real time. On the other hand, instantaneous state changes, external and unforeseen disturbances and model uncertainty and its impact on dynamics can only be taken into account with online approaches as the optimization calculations are performed real time. While offline optimization approached are greatly utilized for helicopter applications, especially for UAVs, [Egerstedt 1999, Frazzoli 2000, Thomas 2010, Jamieson, 2015] the considering the further and future objectives of the study which is generating of green trajectories in terms of noise and fuel consumption for helicopters, an online optimization approach is preferred. Unlike helicopter model simulation, which takes place in time domain, optimization algorithm works in frequency domain to decrease the computation cost. At each execution step, optimization algorithm takes helicopter instantaneous states into account, interrupts the mathematical model, iterates helicopter states that minimize the objective function and generates the desired states until the next execution step. Therefore, helicopter instantaneous dynamic response and conditions are inherently included in the calculations. Besides, any unforeseen disturbances such as wind or mission changes are taken into account as they come to light.

Currently the objective function, i.e. the cost functional, that is minimized at the optimization stage is a combination of getting to target or waypoints, achieving the desired end states, decreasing fuel consumption and avoiding obstacles in the simulation domain. Constrained nonlinear optimization approach with a sequential quadratic programming algorithm which is appropriate for significantly nonlinear systems is utilized for the optimization stage. Spherical avoid regions surrounding the obstacle are defined keeping the obstacle at the center. The avoid regions are divided into two sections. The inner avoid region acts as a hard limit and the aircraft is not allowed to cross the boundary in any circumstances. The outer avoid region is a bumper section, the aircraft allowed to pass however, within which the cost function is dominated by the obstacle contribution while other constraint weights are decreased. This approach eliminates the necessity of constraint definitions for the optimization algorithm.

The optimization objective function concerns the three dimensional distance to the target/waypoint location, heading, flight path angle and sideslip angles to generate optimal guidance reference states. The cost functions are combination of contributions from directional, target state, fuel consumption and avoid region functions and determined through Equation 1 to Equation 5.

$$J = J_{Directional} + J_{State} + J_{FuelCons} + J_{Avoid} \qquad \text{Equation 1}$$

$$\begin{aligned} J_{Directional} &= abs\left[1 - \vec{V}.\left(\vec{r}_{target} - \vec{r}_{hc}\right)\right. \\ &= \vec{V}.\left\{\left(X_{target} - H_{hc}\right)i + \left(Y_{target} - Y_{hc}\right)j \right. \\ &\quad \left.\left. + \left(Z_{target} - Z_{hc}\right)k\right\}\right] \end{aligned} \qquad \text{Equation 2}$$

$$J_{state} = \sqrt{\left(\{S_{target}\} - \{S_{hc}\}\right)^2} \qquad \text{Equation 3}$$

$$J_{FuelCons} = {P_{required}}/{P_{available}} \qquad \text{Equation 4}$$

$$J_{avoid} = \begin{cases} \displaystyle\sum_{i=1}^{\substack{number \\ of\ obstacles}} \sqrt{\left(\overrightarrow{r_i^{obs}} - \overrightarrow{r^{hc}}\right)^2} & if \quad in\ bumper\ avoid\ region \\ \infty & if \quad in\ inner\ avoid\ region \end{cases} \qquad \text{Equation 5}$$

Controller and SAS Stages

Current controller architecture takes reference body u, v, w velocities and heading angle into account and calculates required helicopter collective, longitudinal & lateral cyclic and pedal inputs that minimize the error between helicopter instantaneous states and reference states. The reference states are generated while considering platform specific constraints such as maximum speed, power available, linear and angular acceleration limits. Therefore, it is assured that the platform is capable of reaching the reference states within its aerodynamic and flight dynamics capabilities. Having four control inputs for a typical helicopter, four states are being operated by the controller. The control inputs determined are then operated by the SAS model which basically is a LQR produced on p, q and r rates of the helicopter. As the r component of the LQR and heading tracker of the controller are opposing to each other during the simulation, additional attention was given to tune proper coefficients and gains to compromise.

RESULTS and CONCLUSION

A state feedforward in included in the optimization stage to eliminate the stability and increase robustness of the generated reference states. In this study, a 100% (virtual) state feedforward is utilized. Flight simulations performed with the optimization stage with and without the state feedforward are presented with **Figure 2**.

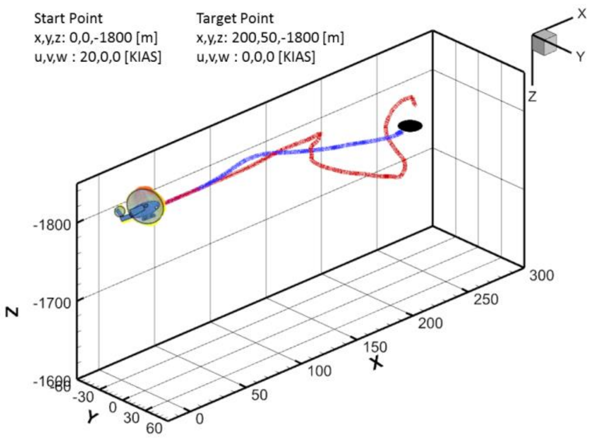

Figure 2 Simulation results with and without state feedforward in the optimization stage [red: without feedforward, blue : with feedforward

Addition of the fuel consumption in the cost functional changes the generated path and simulation results in terms of reduced power requirements. Simulation results determined with and without fuel consumption contribution to the cost function are presented with **Figure 3**. It is determined that, including the fuel consumption concern in the cost function at the optimization stage decreases the fuel consumption 2-3% for a 10 second simulation while still achieving the same target waypoint. For typical mission profiles specific for helicopters, it is observed that, it is possible to decrease the fuel consumption up to %5-6 percent.

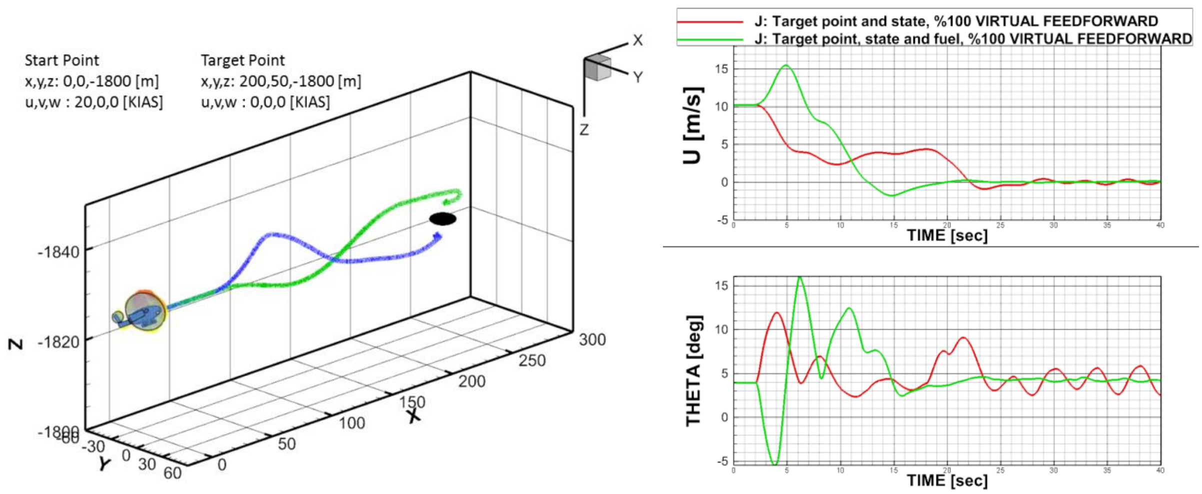

Figure 3 Simulation results with and without fuel consumption concern in optimization stage [blue: without fuel consumption, green : with fuel consumption concern]

How the presence of a single or multiple avoid regions alters the optimal path is studied. Firstly a single avoid region is placed within the simulation domain between the target point and the start point. The helicopter is trimmed at level 20 KIAS forward flight condition, optimal path generation and track performances are evaluated with three different cost functions. Results determined with directional and final states cost function, directional, final state and avoid region cost function, directional, final state, avoid region and fuel consumption cost function are illustrated with **Figure 4**. Multiple avoid region is studied with directional and final state cost function and results are presented with **Figure 5**. The red path represents the generated trajectory in the presence of single avoid region, blue path represents the generated trajectory in the presence of multiple avoid regions.

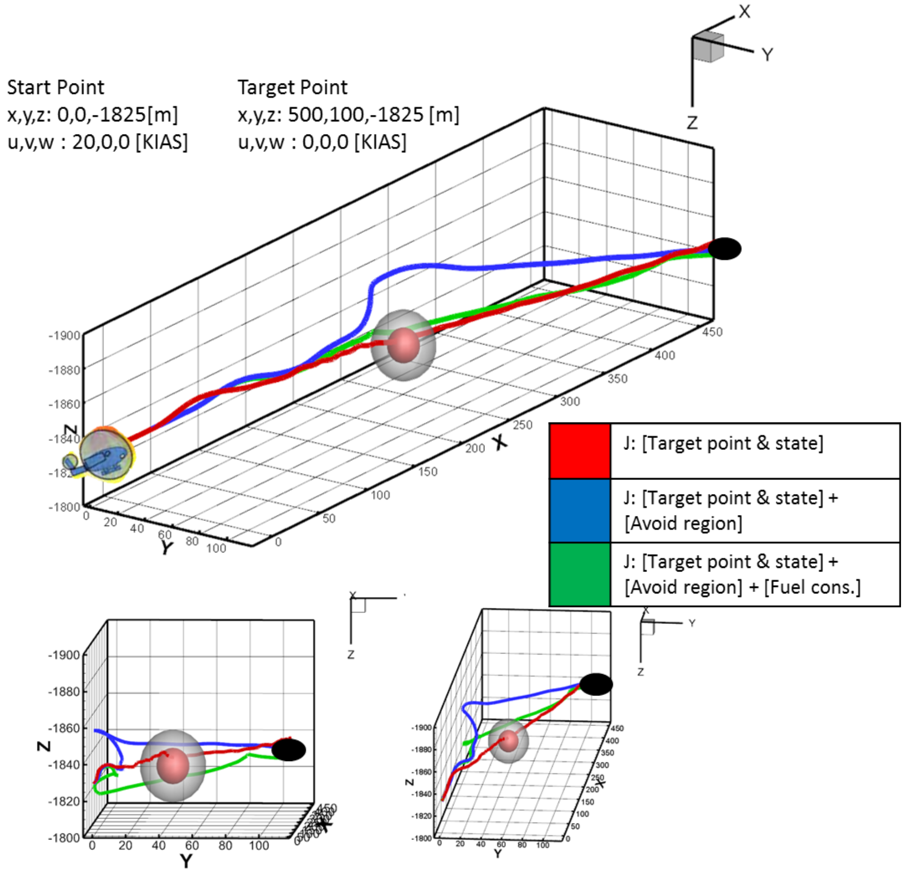

Figure 4 Single avoid region results

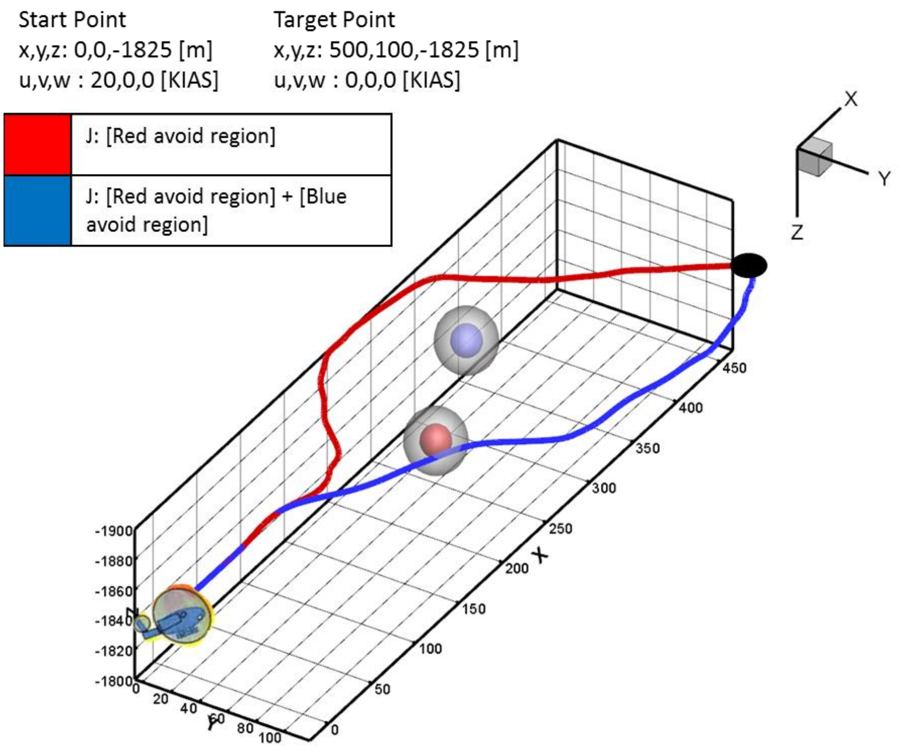

Figure 5 Multiple avoid region results

Finally, multiple target/waypoint calculations and simulations are performed. To study the multiple target case, five waypoints are defined at various altitudes and a hover condition is defined as the target state at waypoint 5. Directional, final state and directional, final state and fuel consumption cost functions are utilized, multiple target/waypoint simulations are performed and generated paths are illustrated with Figure 6.

	X [m]	Y [m]	Z [m]
Initial Cond.	0	0	-1825
Waypoint 1	200	50	-1825
Waypoint 2	300	50	-1825
Waypoint 3	400	0	-1825
Waypoint 4	450	-50	-1855
Waypoint 5	500	-100	-1920

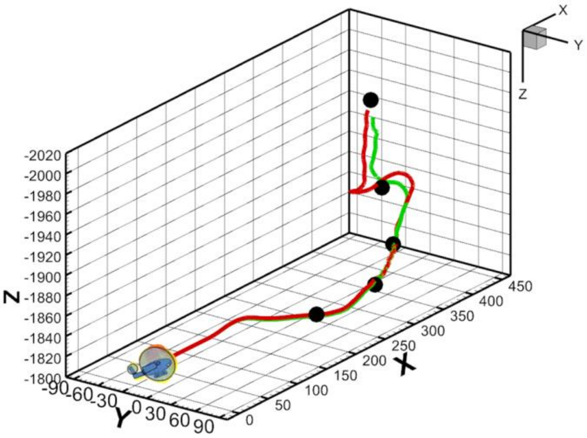

Figure 6 multiple target/waypoint results

In conclusion, a guidance model for helicopter which incorporates the non-linear mathematical model, optimization algorithm, controller and a SAS is developed. Developed model takes target/waypoint and helicopter locations as well as helicopter attitudes into account and determines the optimal flight path in accordance with the various objective functions. While controller and SAS assure that the helicopter traces the reference states, optimization algorithm produces the reference states.

It is experienced that stability problems arise and can be eliminated with a state feedforward at optimization stage. Current study utilizes an ideal state feedforward however, a model predictive stage is planned to be implemented to estimate helicopter future behavior more realistic. Utilizing the avoid regions as cost function instead of as optimization constraints enables taking advantage of bumper regions surrounding the obstacles (inner avoid region). By doing so, a smoother transition of trajectory around the obstacles can be generated.

As future work, aeroacoustic noise and fuel consumption estimation models [Yucekayali 2015] and additional objective functions will be employed on the tool developed with this paper. The optimal guidance model will then be utilized to determine noise minimal and green trajectory generation for helicopters. Furthermore, in order to utilize a more realistic state feedforward in the optimization, a model predictive stage is planned to be implemented. By doing this, it is anticipated that a better representation of the future consequence of the current action will be included in the optimization stage.

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