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Introducing an On-board Guidance Approach forManned Capsules

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ABSTRACT: Reentry capsules (manned or unmanned) have various guidance methods. All of these methods can be divided into three approaches including nominal trajectory pursuit, optimal control optimization, and trajectory optimization. Each of these methods has its own advantages and disadvantages but for on-board applications and robustness to any uncertainties, optimizing the control (optimal control or robust control) is only reliable yet. In this paper, the second approach has been selected for developing a suitable guidance method for a manned space capsule. At first, control optimization problem changes into the line-of-sight control using proportional navigation and nonlinear feed-back control. Then, a suitable procedure has been introduced to apply the proposed method for manned capsules. Finally, for a case study results of trajectory simulation have been presented in the presence of uncertainties and control mechanism limitation with the goal of simultaneously reduction in landing errors and maximum required accelerations. The results confirm the performance and optimality of the proposed algorithm in comparison with the classic methods.

KEYWORDS:Manned space capsule, Reentry guidance, Control mechanism limitation, Reentry Trajectory

I. INTRODUCTION

Simple optimization problems, generally involve in defining the cost functions, optimization parameters, limitations and constraints. Guidance algorithm may be defined loosely as the art of finding the correct acceleration commands to move between two given points which is actually an optimization problem. Different techniques have been suggested for the design of guidance algorithms independent of vehicle's type. These range from the earliest algorithms derived using physical insight (e.g., pursuit, proportional navigation (PN) and their variants) to those derived from a systematic application of mathematical techniques. However, physical limitation, states bound, trajectory limitation and vehicle configuration limit the geometry guidance application. In the other hand, mathematical techniques such as an optimal control or trajectory optimization have disadvantages in facing with system changing or reconfiguration. Reentry vehicles such as manned capsules are always involved in model and reentry states uncertainties. In addition, target point and atmospheric parameters are not completely constant. Finally, structural, aerodynamics and heat transfer constraints should be considered for developing a reentry guidance algorithm.

As review of literature [1..10], various guidance methods have been introduced for reentry vehicles including nominal trajectory pursuit, optimal control optimization, and trajectory optimization. Each of these methods has its own advantages and disadvantages but for on-board applications and robustness to any uncertainties, optimizing the control (optimal control or robust control) is only reliable yet because trajectory optimization approach involve in numerical optimization[1,2,5,6,8,11,12]. We try to use advantages of all introduced guidance focusing on on-board applicability for reentry capsules. In this paper, second approach has been selected for developing a suitable guidance method for manned space capsule. At first, control optimization problem changes into the line-of-sight control using proportional navigation and nonlinear feed-back control. Advantages and disadvantages are introduced. Then, a suitable procedure has been introduced to apply the proposed method for manned capsules. Finally, for a case study results of trajectory simulation have been presented in the presence of uncertainties and control mechanism limitation with the goal of simultaneously reduction in landing error and maximum required accelerations.

II. CONTROL MECHANISM LIMITATION

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Vol. 3, Issue 1 , January 2016

Three parameters can be used to control the reentry trajectory. These parameters are, in fact, keplerian parameters. The control mechanisms should able to change the level of velocity and/or tension of velocity. Generally, four well-known control mechanisms have been used for reentry phase as follow:

1- Thrust vector control
2- Center of mass movement
3- Gas dynamic thrusters
4- Aerodynamics surface

Changes in velocity level and tension of velocity are the benefits of a control mechanism. It has been shown that aerodynamics mechanism has better performance for reentry vehicles based on mass and required volume objectives. This mechanism has been used in many RV scenarios; therefore, the guidance system works well with this mechanism. Two general specification of an aerodynamic mechanism are:

1- Inability in changing measure of velocity
2- normal control forces upon vector of velocity

With the selection of an aerodynamics mechanism, guidance algorithm should develop required controls as aerodynamic forces (lift and side force).

III. INTRODUCTION OF PROPORTIONAL NAVIGATION (PN)

The goal of guidance is restoration of the vehicle to the favorite position. Various guidance methods are known and have been utilized. One of the most important guidance methods is PN which uses parallel guidance law. In the parallel guidance method, one tries to keep LOS (Line of side) parallel with previous state. If the pursuer shoots with perfect inclination, moreover impact, min control effort can be obtained from the following formula: [13,14].

$$c.e. = \int a_c{}^2 t dt \qquad (1)$$

In PN, control acceleration is proportionate with rotation of LOS.

$$a_c \propto \omega_{LOS} \left(\dot{\lambda} \right) \qquad (2)$$

PN can be divided into:

- PPN (Pure Proportional Navigation)
- TPN (True Proportional Navigation)
- BPN (Bias Proportional Navigation)
- GPN (Global Proportional Navigation)
- APN (Augmented Proportional Navigation)
- IPN (Ideal Proportional Navigation)

Two first methods of PN analysis and reentry guidance method are extracted before modifying PN.

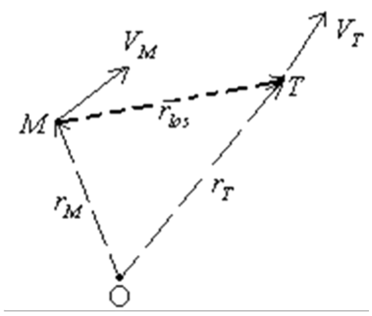

Figure 1 Vector introduction for PN guidance(3 point)

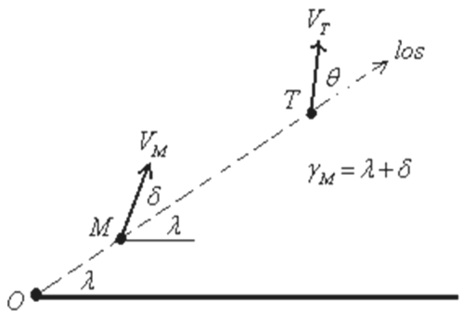

Figure 2 Introduction of PN guidance parameter

PPN:

Control command is achieved with the following sub equation:

$$\begin{aligned}
\vec{r}_{LOS} &= \vec{r}_T - \vec{r}_M \\
\vec{V}_C &= \vec{V}_T - \vec{V}_M \\
\vec{\omega} &= \frac{\vec{V}_C \times \vec{r}_{LOS}}{\vec{V}_C \cdot \vec{r}_{LOS}} \\
\vec{a}_{C_{PPN}} &= N \cdot \vec{\omega} \times \vec{V}_M
\end{aligned} \tag{3}$$

$\overrightarrow{r_T}$: Target position vector, $\overrightarrow{r_M}$: RV position vector, $\overrightarrow{r_{los}}$: LOS vector, $\overrightarrow{V_T}$: Target velocity vector, $\overrightarrow{V_M}$: RV velocity vector , $\overrightarrow{V_C}$: Relative velocity, $\vec{\omega}$: Angular velocity of line of side, N : Navigation constant and $a_{C_{PPN}}$ is Guidance command acceleration

In the PPN guidance method, acceleration (command acceleration) is vertical to RV velocity ($\overrightarrow{V_M}$).

TPN:

This method is similar to PPN but acceleration (command acceleration) is vertical to $\overrightarrow{r_{loss}}$. The relation of respective reminders in continuance is as follows:

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$$\vec{r}_{LOS} = \vec{r}_T - \vec{r}_M$$
$$\vec{V}_C = \vec{V}_T - \vec{V}_M$$
$$\vec{\omega} = \frac{\vec{V}_C \times \vec{r}_{LOS}}{\vec{V}_C \cdot \vec{r}_{LOS}} \qquad (4)$$
$$\vec{V}_{C\parallel} = \frac{(\vec{V}_C \cdot \vec{r}_{LOS})}{\left|\vec{r}_{LOS}\right|^2}\vec{r}_{LOS}$$
$$\vec{a}_{C_{TPN}} = N' \cdot \vec{\omega} \times \vec{V}_{C\parallel}$$

N' : Navigation constant, $\overrightarrow{V_{C_\parallel}}$: Parallel relative velocity and $a_{C_{TPN}}$ is Guidance command accelerations

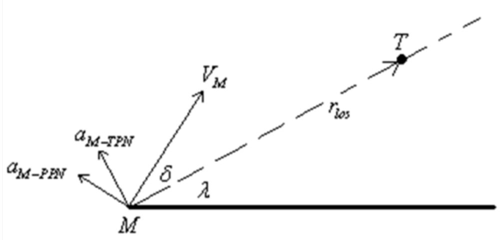

Figure 3 PPN and TPN comparison

IV. MODIFIED PN GUIDANCE FOR RV

For most reentry scenarios, RV velocity vector occurs upside of LOS. PN guidancealways tries to set $\delta = 0$ (figure-2,3) which means $a_c$is in direct of reducing height and causes a shorter flight time. RV's available acceleration can be used to reduce a_c (such as $\vec{g}$); therefore, modifying the PN guidance algorithm for RV is proposed as follows:

1- Guidance acceleration calculated with PN (PPN, TPN,…) . This guidance acceleration has a directional ($\overrightarrow{a_m}$) due to inertial coordinate.
2- RV has acceleration vector ($\overrightarrow{a_{avi}}$) that has been produced by aerodynamics and gravitational forces.
3- The difference between two vectors is considered as a guidance acceleration,(absolutely this vector is in inertia coordinate).

$$\vec{a}_{MPPN} = \vec{a}_m - \vec{a}_{avi}$$
$$\vec{a}_{req} = \vec{a}_{MPPN} \qquad (7)$$

With this teqnique, RV guidance can be considered without acceleration in the PN algorithm. Consequently, RV can now utilize the PN claim (optimum guidance method). The simulated results show that landing point error and constant navigation values reduce after this modification. Modification of the PN algorithm is useful also if the velocity ratio is near one ($\frac{\vec{v}_M}{\vec{v}_T} = 1$). This is described a smaller RV final phase speed.

V. MATHEMATICAL 3D GUIDANCE COMMAND MODELING

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Vol. 3, Issue 1 , January 2016

The PPN method is the best PN method to apply because of the aerodynamics mechanism selection. The modification of PPN can be considered as this sub algorithm:

$$\vec{a}_{MPPN} = N \cdot \vec{\omega}_{LOS} \times \vec{V}_m - \frac{1}{m_{R.V}} (\vec{L} + \vec{D} + \vec{S}) - \vec{g} \qquad (8)$$

In order to calculate the sub algorithm requiring guidance acceleration, $\vec{a}_{MPPN}$ must be changed to a body coordinate. DCM is used to accomplish this [19].

$$\vec{a}^{W}_{req} = C^{W}_{I} \vec{a}_{MPPN} = a_1 \hat{e}_D + a_2 \hat{e}_L + a_3 \hat{e}_S$$
$$C^{W}_{I} = \begin{bmatrix} c_{11} & c_{12} & c_{13} \\ c_{21} & c_{22} & c_{23} \\ c_{31} & c_{32} & c_{33} \end{bmatrix} \qquad (9)$$

The first component should exit without changing because of the control mechanism. The second and third components introduce a control command.

$$\vec{a}_C = a_2 \hat{e}_L + a_3 \hat{e}_S \qquad (10)$$

At last, aerodynamics control forces (respective angle of attack and side slip) are easily calculated.

$$C_L = \frac{a_2 \cdot m_{r.v}}{qS} = f(M, \alpha) \ , \quad C_S = \frac{a_3 \cdot m_{r.v}}{qS} = g(M, \beta) \qquad (11)$$

VI. REENTRY SCANARIO

The scenario and RV parametersare considered as follow:

$h = 200\,km$

$Lat_{Deorbit} = 0^{\circ}$

$Long_{Deorbit} = 40^{\circ}\,E$

$V = 5512\,m/s$

$M_{RV} = 255$

For better guidance methods comparison, reentry parameters have maximum error ($\pm$10% h error& v error & gamma error $\pm 5^0$). Maximum reentry states error lead to have two worst cases that are introduced in table (1).

Table (1) Max Reentry error and range condition

error (Km)	Reentry altitude (Km)	Reentry velocity (m/s)	Reentry angel (γ)	Error condition
+1381	220	6063.2	$+5^{\circ}$	Max Range
-625	180	4960.8	-5°	Min Range

It is clear that max range condition has a large error and is more critical. This condition is therefore selected for evaluating the performance of different guidance methods.

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Vol. 3, Issue 1 , January 2016

VII. TRAJECTORY RESULT

6DOF simulation has been used to derive the guided reentry trajectory for classic PPN and proposed algorithm. Supporting graphs are as follows:

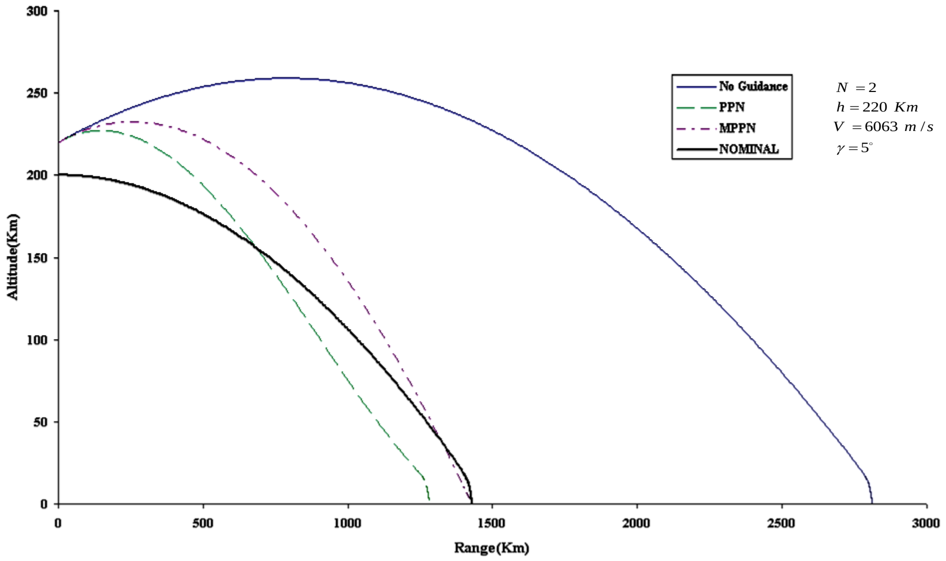

Figure 4 Range – Altitude chart for PPN and MPPN comparison

Figure-5 shows trajectory of MPPN converge to nominal trajectory in terminal phase when classic PPN has wide error.

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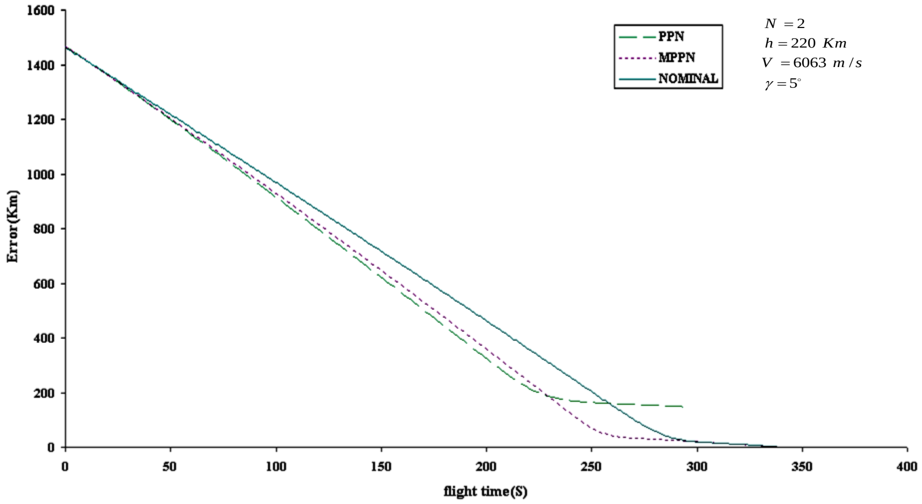

Figure 5 Error of descent point for PPN and MPPN

Figure-6 shows descent distance for both guidance methods. It is clear that PPN has a wide range of error. One of the basic reasons for this error is the decrease of velocity ratio ($\frac{V_M}{V_T}$) near one. Therefore, RV difficulty can follow the landing point in PPN because requires acceleration proportionatewith RV velocity.

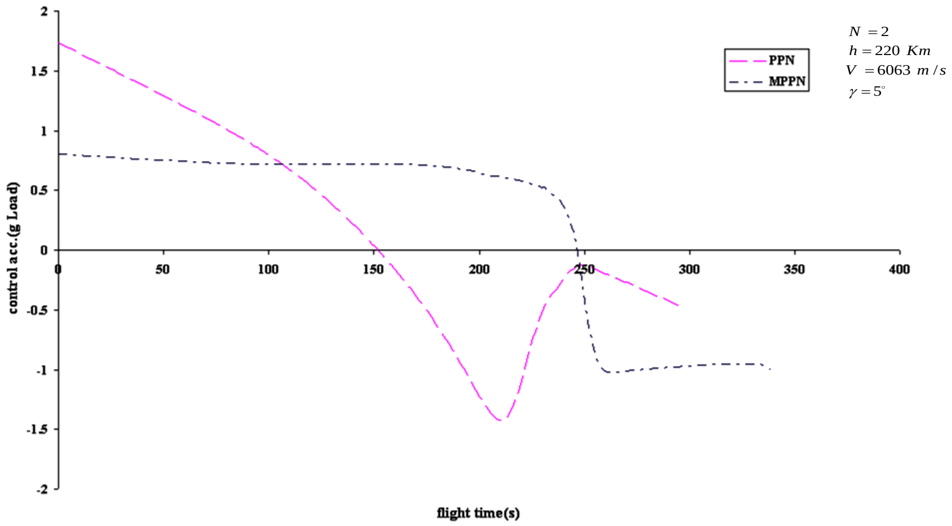

Figure 6 Control acc. Command of PPN and MPPN

The most important chart of 6DOF simulation of guided trajectory is the required guidance acceleration. Figure-7 confirms the optimality claim of MPPN.

MPPN method calls lower maximum required acceleration and has little veer from initials acceleration when PPN requires higher maximum acceleration and has wide variation.

For both algorithm, it can be seem that sign of guidance commands has been changed. This point is disadvantages of both algorithm and should be compensate by changing the constant navigation parameter. Comparisons of the results have been summarized in table (2).

Table (2) Comparison between the proposed algorithm and PPN

Total flight time (s)	Control effort (m/s)	Max guidance acc. (g load)	Impact error (Km)	Guidance method
295.92	2258	1.731	147.24	PPN
340.15	2519	1.207	0.004	MPPN

VIII. SUMMARY AND CONCLUSION

In this paper, a suitable guidance method for manned space capsule has been developed based on control-of-sight approach using proportional navigation and nonlinear feed-back control. It has been shown that classic PN algorithm is not suitable for application in reentry phase. In addition it cannot consider the required limitation and constraints itself because it does not use the system model. Then, a suitable procedure has been introduced to be applied for reentry capsules with the goal of simultaneously reduction in landing error and maximum required accelerations. For a case study, results of trajectory simulation have been derived in the presence of uncertainties and control mechanism limitation.According to the results, the proposed algorithm has 4m error in landing while classic PN has 147km error. In addition, the proposed algorithm demands 1.2 g-load but PN needs 1.7 g-load. The results confirm the performance and optimality of the proposed algorithm in comparison with the classic PN.

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