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Araştırma Makalesi / Research Article

Lunar Excursion Module Landing Control System Design with P, PI and PID Controllers

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Abstract
The development of space technology has always been one of the most exciting areas of science. System, used in the Moon Landing of mankind, became worth examining with developing technologies. In particular, developments in control systems theory have led to significant successes in the control of highly complex systems. It is also possible to re-examine the performance of this system, which is quite costly, by using simulation methods. The vehicle is called as the Lunar Excursion Module (LEM), which brings the astronauts down to the Moon's surface from the space vehicle in the Moon's orbit. Proportional (P), proportional-integral (PI) and proportional-integral-derivative (PID) controllers were prepared for the safe descent of the lunar navigation module modeled using MATLAB / Simulink computer software. These selected controllers ensure that the individually controlled LEM operates in accordance with the rules set out in the current landing procedure in the literature. The most appropriate coefficients for the controllers were selected by using the system response curve and continuous vibration methods and their performances were compared in detail.

Keywords: Lunar excursion module, PID control, System response curve method, Continuous vibration method

Ay Gezinti Modülünün İniş Kontrol Sisteminin P, PI ve PID Denetleyicilerle Tasarımı

Öz
Uzay teknolojisinin gelişimi bilimin her zaman en heyecan verici alanlarından biri olmuştur. İnsanlığın Ay yüzeyinde kullandığı sistem, gelişen son teknolojilerle tekrar incelenmeye değer hale gelmiştir. Özellikle kontrol sistemleri teorisindeki gelişmeler ile oldukça karmaşık sistemlerin denetimleri üzerinde ciddi başarılar sağlamıştır. Ayrıca, oldukça maliyetli olan bu sistemin performansını, benzetim yöntemlerini de kullanarak tekrar inceleme olanağı da bulunmaktadır. Bu çalışmadaki incelenen araç, astronotları Ay'ın yörüngesindeki uzay aracından Ay'ın yüzeyine indiren Ay Gezinti Modülü (LEM) olarak adlandırılır. MATLAB/Simulink bilgisayar yazılımında modellenen ay gezinti modülünün Ay'ın yüzeyine güvenli inişi için oransal (P), oransal-integral (PI) ve oransal-integral-türev (PID) denetleyicileri hazırlanmıştır. Denetleyiciler tarafından kontrol edilen LEM'in literatürdeki mevcut iniş prosedüründe belirtilen kurallara uygun olarak çalışması sağlanmıştır. Denetleyiciler için en uygun katsayılar sistem cevap eğrisi ile sürekli titreşim metotları kullanılarak seçilmiş ve bu denetleyicilerin performansları detaylı olarak karşılaştırılmıştır.

Anahtar Kelimeler: Ay gezinti modülü, PID kontrol, Sistem cevap eğrisi metodu, Sürekli titreşim metodu

1. Introduction

Although reality is still controversial today, US President John F. Kennedy's announcement of his appointment to the Moon is an important milestone for space technology. Through the intensive efforts of many scientists and the realization of a special machine, a man's lunar mission ensured that a person returned from Earth to the Moon and returned safely back. Even today, for many scientists, this machine is considered to be an unrivaled work in the field of engineering. In this process, three complex tools were created to work together seamlessly to achieve an unlikely goal. These complex tools are Saturn V rocket, Apollo Command and Service Modules (CSM) and Lunar Excursion Module (LEM) tools that provide moon shots.

During the mission of sending people to the Moon, Saturn V rocket, the most powerful propulsion system of humanity, enabled the Command Module (CM) to travel safely to the Moon and return to the Pacific Ocean with three team members. The mission of the Lunar Excursion Module is to go back to the Moon with a group of people and return them to their orbit after completing their tasks (Stengel, 1969).

The most important part of the LEM's mission is landing. It must travel along the targeted path in space and move slightly into the Moon. This may seem difficult, but a simple mistake can cause the crew to lose their lives. So for a safe landing, a soft landing that will not hurt the crew and the crew, and the legs all have to stand upright by hitting the moon ground at the same time. In addition, the pilot should be able to make last-minute corrections if necessary. A photograph taken on the Moon during the LEM mission is given in Figure 1.

Figure 1. An image taken during the mission of the Lunar Excursion Module (LEM) (NASA, 2018).

2. Main Systems of LEM

The Lunar Excursion Module has complex system dynamics. The control system for Lunar Excursion Module landing consists of three main sections. The first landing drive system includes an engine with propulsion power between 1050 and 10125 lbs. The second system, the reaction control system, consists of 16 propulsion cells (they cannot throttle up or down) with a thrust of 100 pounds. Both of these systems use fuel aerosol 50 and oxidizing nitrogen tetroxide. Finally, the sensors in the Lunar Excursion Module track the position and direction of the Lunar Excursion Module using the radar sensors of the Lunar Excursion Module and an optical telescope during landing (Smyth, 1965). The landing gear must provide sufficient energy -absorption capability and adequate vehicle -toppling stability for the range' of possible touchdown conditions and for the lunar surface characteristics defined in the technical specification. On the lunar surface, the landing gear must prevent impact of the descent-stage base heat shield, fuel tanks, and plumbing with the lunar surface; however, the descent-engine skirt may contact the lunar surface (Rogers, 1972).

2.1. Descent Propulsion System

It has a rocket motor that can slow down the LEM's landing speed to 5 ft/s. There is a gas control on this rocket. This controller can allow the LEM to increase its current thrust to 10125 lbs. from 1050 lbs. This rocket also has the ability to restart the pilot's command. This function is an additional measure if any unexpected condition occurs during the first landing of the LEM during the orbit change. This propellant is loaded with aerosol 50 and nitrogen tetroxide as fuel and oxidizer. They are carried in a total of four tanks at the bottom of the LEM (Lunar Module, 1969). The system components and fuel tanks that make up the Descent Propulsion System are shown in Figure 2.

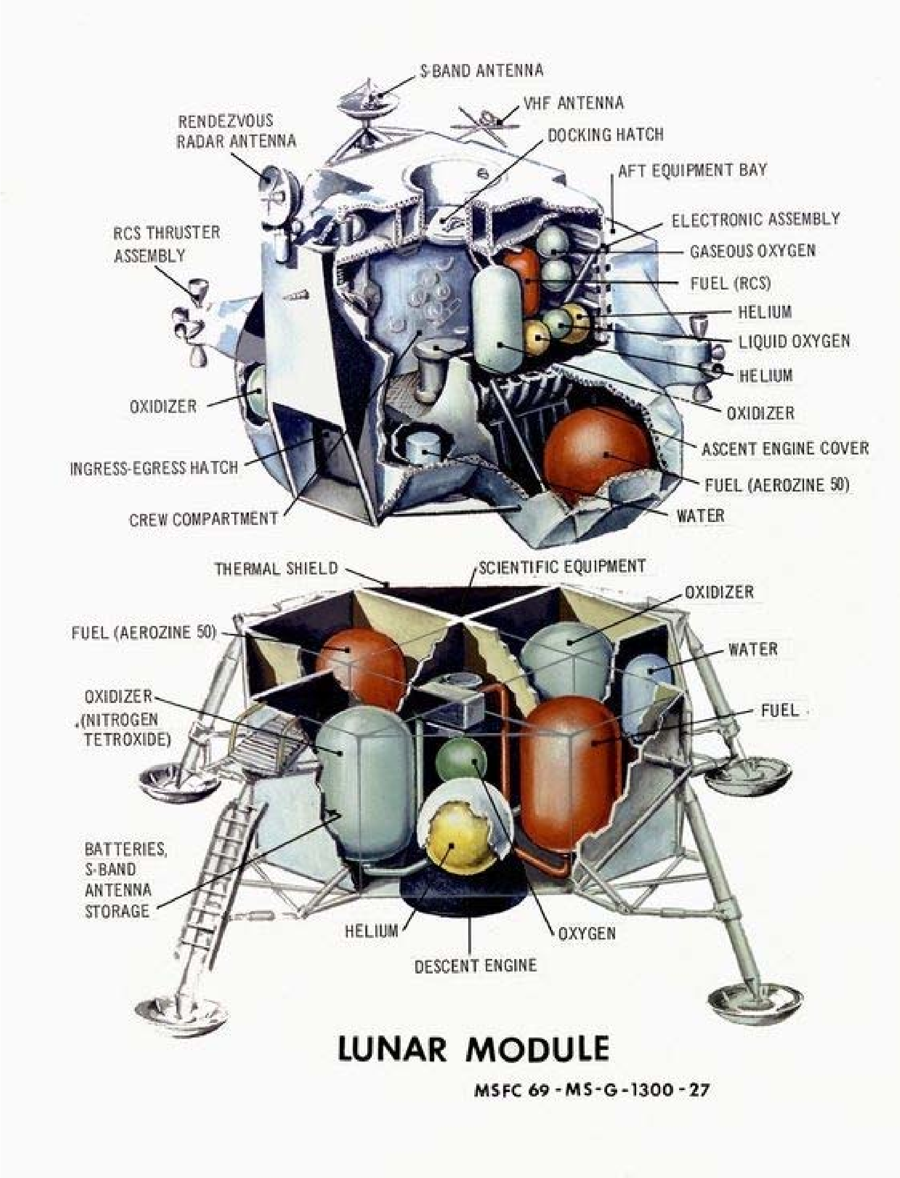

Figure 2. An overview of the landing gear system (NASA, 2018).

2.2. Reaction Control System (RCS)

The Reaction Control System (RCS) controls thrust strokes, attitude and rotation during the landing and exit trajectory, balancing the LEM during accentuated landing, meeting, around the three axes of the vehicle. The RCS also provides the thrust required to separate the LEM from the CSM and the +X-axis acceleration required to settle Main Propulsion Subsystem (MPS) propellants before a descent or ascent engine start. The RCS accomplishes its task during coasting periods or while the descent or ascent engine is firing; it operates in response to automatic control commands from the Guidance, Navigation, and Control Subsystem (GN&CS) or manual commands from the astronauts(Chilton, 1965).

The Reaction Control System (RCS) is a highly complex part of the LEM design. It consists of 16 push cells that are used to control the navigation and tracking of the LEM away from the Command Module (CM) during the operation. There are four different rows of chambers to create the right forces at the right time to steer during the ascension and descent of the spacecraft. This is much smaller than the landing ramp, each producing only 100 pounds of thrust. They can only provide firing for minor adjustments in direction and direction. The system uses a propellant mixture identical to the landing propulsion system and has its own tanks that hold fuel and oxidizer. There is an important difference between RCS pushers and landing pushers. RCS pushers cannot be suppressed in any way; which always produces a thrust of 100 lbs. when fired (Arney et al., 2004). The Reaction Control System is shown in Figure 3.

Figure 3. A general view of the Reaction Control System (RCS) (NASA, 2018).

2.3. Guidance and Navigation Sensors

A number of sensors are needed to track information about the LEM's position and orientation so that the landing sequence is automatically controlled. This is accomplished by a series of radar sensors and an alignment optical telescope. Radar sensors are mostly used during CM communication and landing. It also provides information about LEM elevation, landing speed, and a measurement of three offset angles (pitch, roll and yaw). The optical telescope is primarily used to find a suitable landing area (Lugo, 2004).

3. LEM Landing Procedure and Orientation Control Parameters

The LEM leaves the Command Module at a height of 8000 feet from the surface of the moon. The LEM falls free to the Moon surface at an altitude of 2000 ft, at which time the crew will make the final check of the equipment before the stopping point is reached. At an altitude of 2000 ft, repulses begin to improve the direction and speed of the LEM. The RCS explosives are fired in pairs to direct the LEM correctly, so that the four females hit the surface of the moon at the same time. At this critical altitude, the speed of the LEM is 250 ft/s. From this point, the LEM reaches the desired speed in about 15 minutes. This is done by the landing engine. The landing engine explodes the LEM with variable thrust forces to slow it down to 5 ft/s to avoid damage to the system. RCS traverses the LEM before landing on the Moon's surface. For the mechanical strength limits of the LEM, the angular speed limit is fixed at a fixed roll and pitch of 10 degrees/s (0.174533 rad/s). During the landing of the LEM, the control of the angle of rotation is ensured, although the control of the yaw angle and tilt angle is very important. The angular velocity restriction is adjusted to provide manual thrust control of the pilot of the LEM when it reaches the correct orientation as the LEM, roller or curtain. In this control system, RCS actuators, actuators and LEM are the system itself. Due to the constraints of the physical design of the RCS impulse, a step function controller should be used (Apollo 9, 1999; Johannes et al., 2018; Liu et al., 2017). The force axes acting on the Lunar Excursion Module (LEM) are shown in Figure 4 on the LEM prototype.

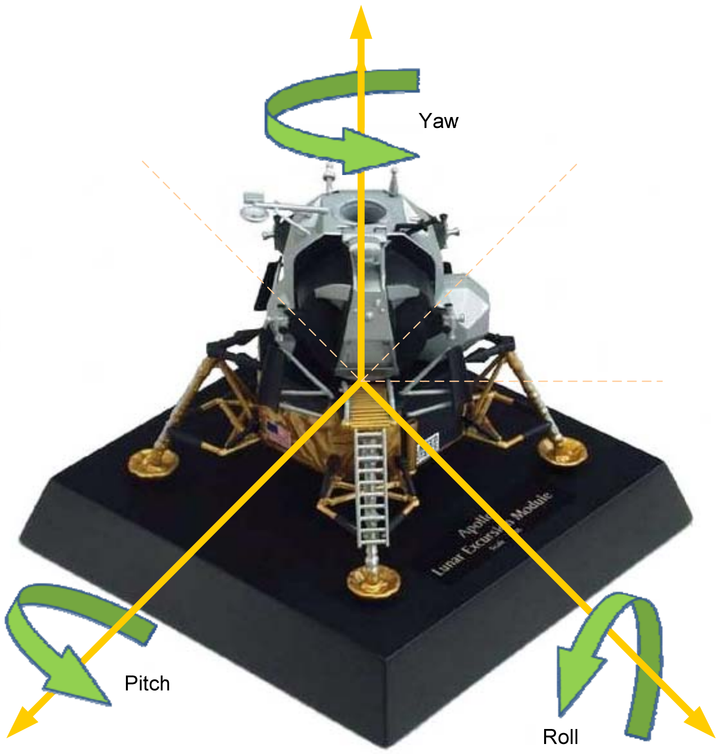

Figure 4. Indication of the force axes acting on the LEM (NASA, 2018).

4. Mathematical Model of LEM

In the Lunar Excursion Module, the landing speed is controlled by gas nozzles mounted on the plows. Spray makes repellent imbalance. Make the imbalance of spray propellants. A simplified view of the system is given in Figure 5.

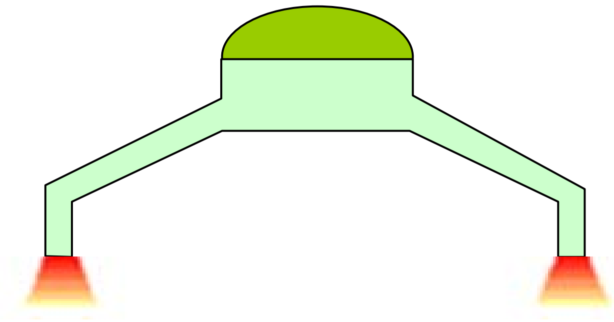

Figure 5. Simplified shape of lunar excursion module.

It can be assumed that the torque applied by the gas sprays is proportional to the voltage applied to the jet control. The nozzles of the LEM operate unstably, keeping the total force constant so that the height is maintained. The transfer function of a mathematical model of a LEM is given in Equation 5.1 (Kwon et al., 2016; Zhang and Duan, 2013; Mueller et al., 2012; Orr and Shtessel, 2012; Mueller, 2011).

$$G(s) = \frac{w_n^2}{s^2+2\zeta w_n s+w_n} \quad (1)$$

For the safe and comfortable landing of the LEM's human pilots, the system parameters must be selected as given in Table 1 (Brown et al., 2010; Bilimoria, 2009; Thurman and Flashner, 1996; Thurman and Flashner, 1996; Stengel, 1993; Klumpp, 1974).

Table 1. Information on system parameters.

Parameters	Symbol	Value
Damping Ratio	ζ	0.7
Natural Frequency	ω_n	0.5

5. LEM Control System

Methods such as Bode, Nyquist, amplitude-phase curves and Nichols, which are used in the design of linear systems, do not need detail in the drawings. Thus, high-order systems can be designed even by using the frequency domain criterion such as gain share, phase share, resonance peak. On the other hand, behavioral criteria such as rise time, delay time, settling time, overrun in the time definition zone can be analytically designed only in second order systems, and can be approximated in terms of second order systems. For P, PI and PID controller; The setting of the parameters is done in such a way as to provide a matching between the system's persistent state and its dynamic behavior. In determining these parameters, practical determination method, vibration method (experimental method) and system response curve methods can be used (Bolton, 1998).

5.1. Proportional (P) Control

The proportional controller consists of a control signal, a simple amplifier with a gain of k. This structure is called the proportional controller (P) since the input signal P is transmitted at a fixed ratio to the controller output. The proportional controller can also be thought of as an amplifier whose gain is constant. Because of this structure, its application is quite simple. However, there is always a steady state error in the proportional control, and the size of this error depends on the system (Zenk, 2019). The output of the proportional controller is obtained by multiplying the error value at the controller input by a certain coefficient (K_p). The error signal e (t) is used as the input signal. The system output is $X(t) = K_p.e(t)$. K_p is defined as the gain of the proportional controller (Grassi et al., 2000).

5.2. Proportional-Integral (PI) Control

Integral effect removes permanent status errors that may occur in the controlled output size. The integral effect provides an adequate control effect on the changing demands of the intended use system. If the requested demand from the system can be met with a proportional (P) effect on its own, it is unnecessary to use the Integral (I) effect. If I (integral) effect is added to the P (proportion) effect, the PI Controller is obtained. Since the PI controller output has a continuously increasing control effect (integral), it is necessary to change the controlled parameter so that the fault is removed from the center. The resultant deviation is then reset to zero (Kuo, 1999). PI type controller structure is widely used in pressure, level and flow control (Zenk and Akpinar, 2013).

5.3. Proportional-Integral-Derivative Control (PID) Control

It is a Control effect that combines the advantages of the three basic Control effects into a single unit. The integral effect increases the response speed for the same relative stability of the system, depending on whether the PI control effect is used in the derivative effect while resetting the permanent state error that may occur in the system. Accordingly, the PID control system provides a quick response with zero permanent state error in the system (Liu et al., 2017). If a system tuned with the PI Controller will affect large intrusive inputs within a wide range of time intervals, the PI effect alone will not be sufficient to track and correct the variations occurring in the line alone. In this case, the addition of a derivative effect will speed up the controller response time, ensuring that the proportion gain setting is kept higher. Thus, while the PID controller is resetting the permanent state error from one side, the transient state behavior of the system is improved on the other side (Sarıoğlu, 1999).

5.4. System Response Curve Method (SRCM)

A closed circuit loop system that reduces the speed from 250 ft/s to 5 ft/s for the LEM is given in Figure 6. The reaction generated in Matlab/Simulink environment for such a long time without supervision is given in Figure 7.

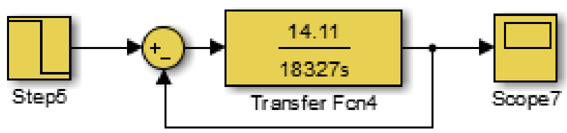

Figure 6. A closed-loop control system block diagram in which a variable referenced input is connected to the transfer function of the LEM.

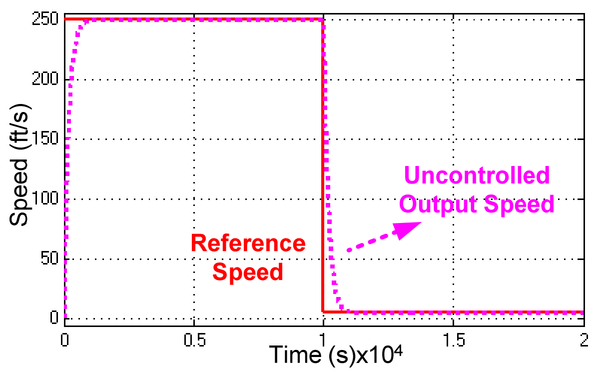

Figure 7. The response curve of the transfer function of the LEM to a variable reference.

Table 2. Controller coefficients obtained by using System Response Curve Method (SRCM)

Controller Type	K_P	T_I	T_D
P_{SRCM}	6.875	-	0.7
PI_{SRCM}	5.500	$9x10^{-3}$	0.5
PID_{SRCM}	8.250	$3x10^{-3}$	$0.2x10^{-3}$

The effects of P, PI and PID controllers on the LEM descent rate using the coefficients in Table 2 are shown in detail in Figure 8.

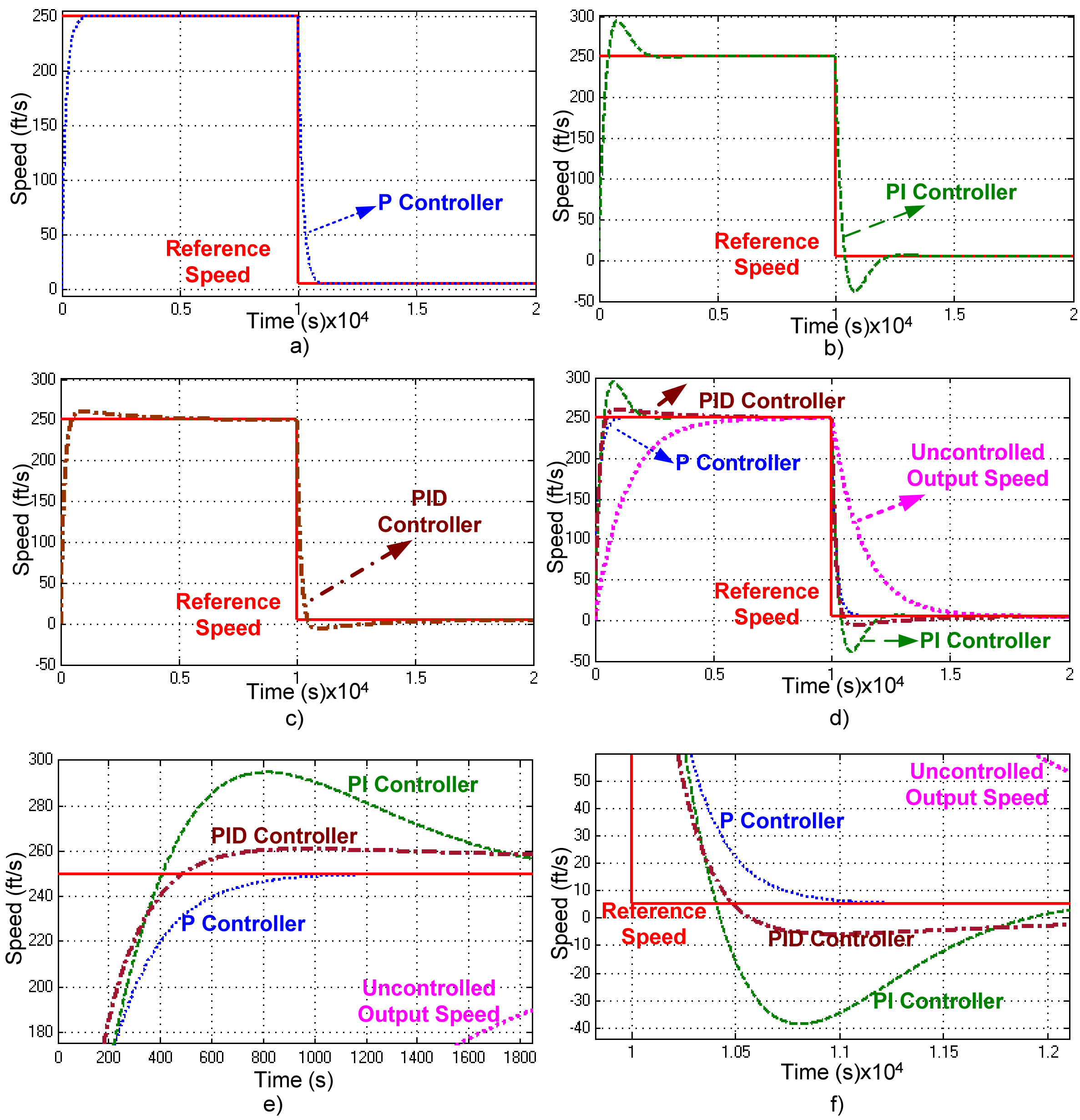

Figure 8. Graph of the results obtained in the case of using the controllers given the coefficients in Table 2 for the speed of LEM, a) the speed of the LEM when the P controller is connected, b) the speed of the LEM when the PI controller is connected, c) the speed of the LEM when the PID controller is connected, d) Reference signal, uncontrolled state, comparison of the effects of P, PI and PID controllers on the speed of LEM, e) The response of the controllers when leaving the LEM at 250 ft/s reference, f) The condition of the controllers when the speed of the LEM is lowered to the reference of 5 ft/s.

5.5. Continuous Vibration Method (CVM)

The integral effect increases the response speed for the continuous vibration method developed by Ziegler and Nichols is one of the experimental methods. This method is based on the fact that the control organ is experimented only with the proportionality effect by deactivating the integral and derivative effects at the beginning. The proportional gain KP for the PI controller is only 10% smaller than that predicted by the proportional type (Kwon et al., 2016). This is because the integral effect reduces the stability of the system by adding phase delay to the system. The coefficients of the controllers designed using the Continuous Vibration Method (CVM) is given in Table 3. The effects of P, PI and PID controllers on the LEM descent rate using the coefficients in Table 2 are shown in detail in Figure 8.

Table 3. Controller coefficients obtained by using Continuous Vibration Method (CVM)

Controller Type	K_P	T_I	T_D
$P_{\underline{CVM}}$	6.111	-	0.7
$PI_{\underline{CVM}}$	6.000	$9x10^{-3}$	0.5
$PID_{\underline{CVM}}$	3.667	$5.294x10^{-5}$	$1.3235x10^{-5}$

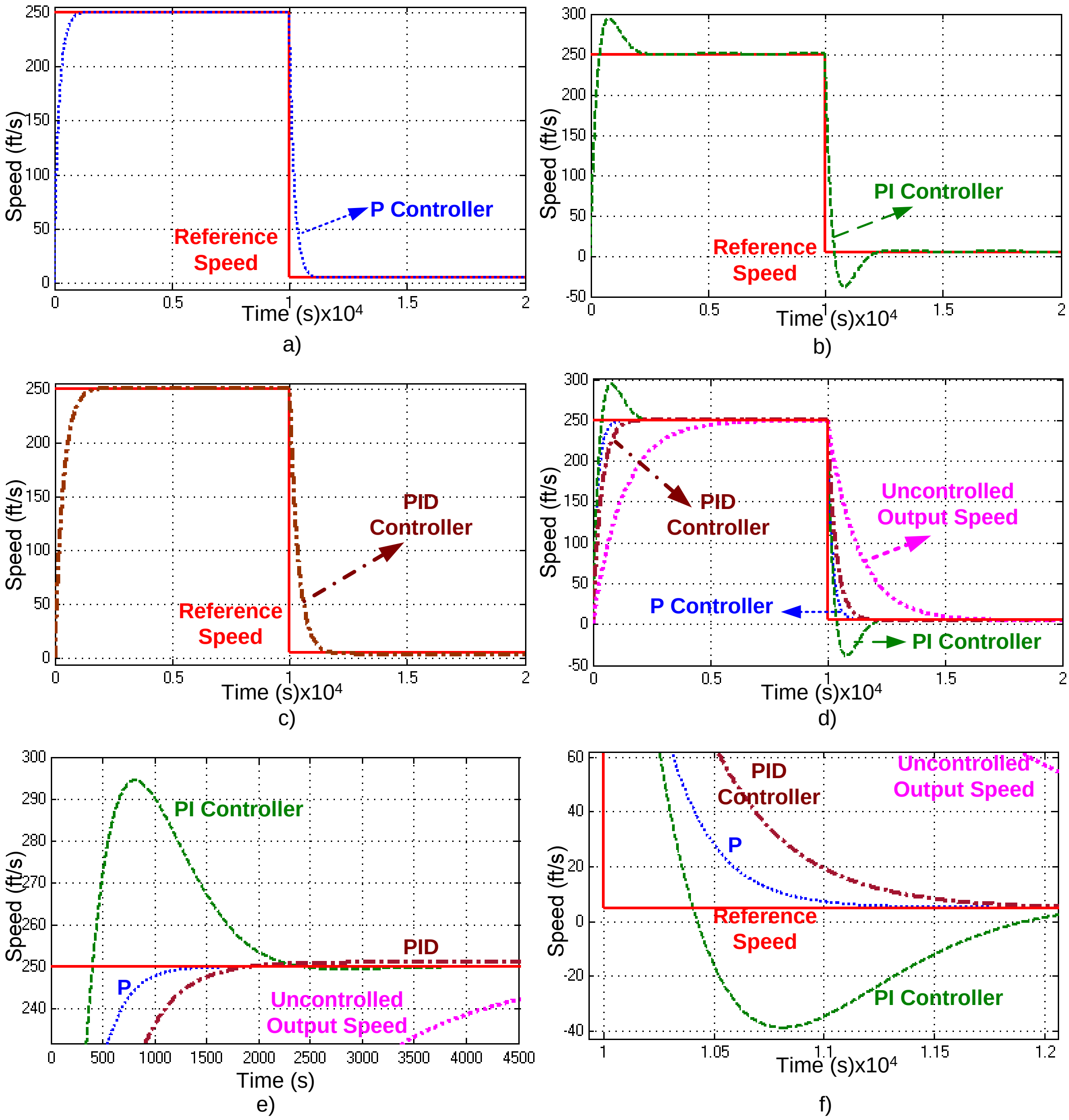

Figure 9. Graph of the results obtained in the case of using the controllers given the coefficients in Table 3 for the speed of LEM, a) the speed of the LEM when the P controller is connected, b) the speed of the LEM when the PI controller is connected, c) the speed of the LEM when the PID controller is connected, d) Reference signal, uncontrolled state, comparison of the effects of P, PI and PID controllers on the speed of LEM, e) The response of the controllers when leaving the LEM at 250 ft/s reference, f) The condition of the controllers when the speed of the LEM is lowered to the reference of 5 ft/s.

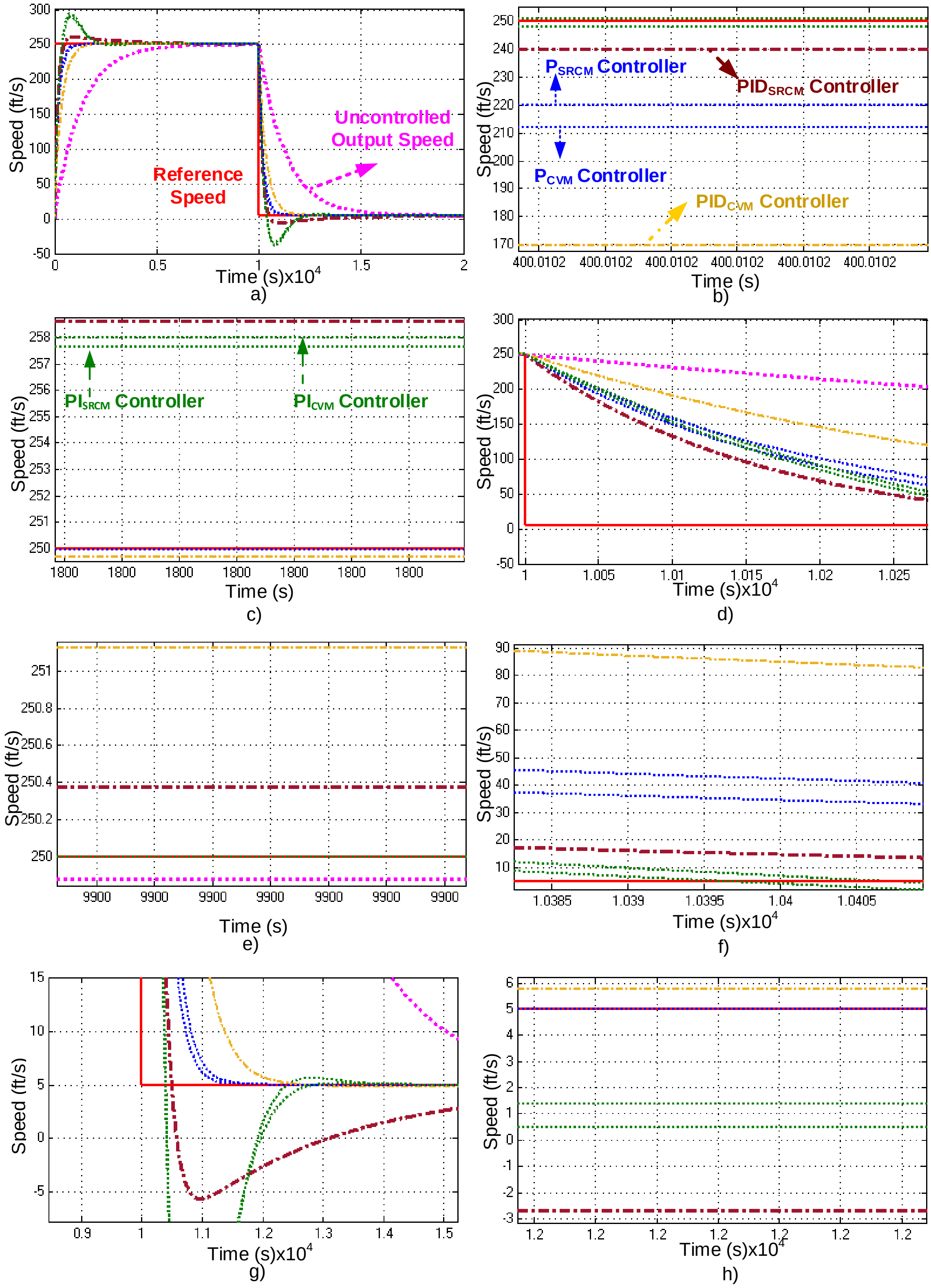

Figure 10. Graph In order to compare the performances of the controllers of the Lunar Excursion Module with different methods, speed information graphics (ft/s) generated at selected time values, a) Overview of the complete reference effect when the entire controller is connected, b) Examination of the situation at the 400th second, c) Examination of the situation at 1800th, d) Examination of the range of 1-1.025x10^4, e) Examination of the situation at 9900, f) Examination of the area between 1.0385-1.0405x104, g) Examination of the range of 0.9-1.5x104, h) Examination of the situation at 1.2x104 sec.

In Figure 10, the Moon Navigation Module (LEM) provides the ability to compare the results produced by the P, PI and PID controllers designed with two different methods to control the descent of the transfer function, giving the speed information at the sampled times given together with reference and uncontrolled system response. The controllers used in Table 4 are given speed information at 400th, 1800th, 9900th and 12000th seconds from the moment the system starts. The P controller showed a System Response Curve Method (SRCM) calculated that the response closest to the reference in 12000th seconds.

Table 4. A numerical representation of the effects of the LEM's speed on the selected time values of controllers using different methods.

Method	Controller Type	400th s	1800 th s	9900 th s	12000 th s
System Response Curve (SRCM)	P_{SRCM}	219.9089	249.9818	250.0000	5.0000
Continuous Vibration (CVM)	P_{CVM}	211.9280	249.9475	250.0000	5.0201
System Response Curve (SRCM)	PI_{SRCM}	248.0844	257.6390	250.0000	1.3850
Continuous Vibration (CVM)	PI_{CVM}	250.9887	257.9895	250.0000	0.4748
System Response Curve (SRCM)	PID_{SRCM}	240.2659	258.6396	250.3754	2.6735
Continuous Vibration (CVM)	PID_{CVM}	169.5743	249.6629	251.1248	5.7501

6. Conclusions

In this study, the vehicle known as the Lunar Excursion Module is separated from the CM moving from the moon orbit. After reaching the shooting area of the Moon, the velocity reaches 250 ft/s and then the system response curve and continuous vibration methods Various P, PI, and PID coefficients were obtained. It was provided with all controllers that the system is desirably kept within the limits in the landing procedure. However, if the performances of the controllers are compared, the best response is proportional controllers (P). The controllers which were prepared by two different methods gave the controller prepared by the best response system response curve method. Although the PI controller's steady state reference approach is better than the PID controller, the transient state overload is too high. The responses generated by the PI controllers are very close to each other, and if a comparison is made between them, it is understood that the values produced by PI_{SRCM} was at a better level than PI_{CVM}. The performance of PID controllers was also very good. However, the system response curve method, which responds better to other controllers, gave worse results than the controller prepared by the continuous vibration method in the PID controller.

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