# Conceptual Study of 6 DOF Precision Control of Payload Using 6 Axis Hybrid Actuator

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Concept of 6 degree-of-freedom (DOF) precision control of payload, which utilizes 6 axis hybrid actuators between the payload and the spacecraft bus, is presented. This type of control system is thought to be especially suitable for the payload that requires very demanding pointing accuracy, such as a space telescope. The advantages of using hybrid actuators that consist of passive vibration isolator and active actuator elements are: (1) realization of ideal vibration isolation between the payload and the bus, (2) capability of direct control of the pointing or the attitude of the payload, regardless of attitude accuracy of the bus, and (3) fail-safe capability as a passive isolator in case of any failure of active actuator elements. The system concept is stated and then some fundamental properties of the system are derived, based on a simple two rigid-body model with basic control schemes. The system is also compared with related systems and concepts from the viewpoint of system architecture, functions and properties so as to clarify the essential features of the system.

**Key Words:** Pointing Control, Attitude Control, Inertial Stabilization, Vibration Isolation

## Nomenclature

| | |
|---|---|
| P | : payload |
| B | : spacecraft (S/C) bus |
| A | : pure or hybrid actuator(s) (massless) |
| S | : total system (=P+B+A) |
| _* | : center of mass (CM) of the body _ |
| IS | : inertial sensor(s) of P (and also B, if any) |
| RS | : relative sensor(s) between P and B |
| PS | : pointing sensor of P |
| AS | : attitude sensor(s) of B |
| X,Y,Z | : coordinates of inertial reference frame |
| $m$ | : mass |
| $I$ | : moment of inertia (MOI) |
| $x$, $z$ | : position (displacement) along X and Z |
| $\theta$ | : attitude (angular displacement) about Y |
| $a$ | : acceleration |
| $f$, $t$ | : force and torque |
| $l$ | : length of moment of arm |
| $F(s)$, $G(s)$ | : transfer function where $s$ is the variable of Laplace transform |
| $T(\omega)$ | : transmissibility (=$\lvert F(j\omega)\rvert$ etc.,) |
| $\omega$ | : angular frequency |
| Subscripts | |
| $P$ | : payload |
| $B$ | : S/C bus |
| $S$ | : total system (=P+B+A) |
| $d$ | : disturbance on P or B |
| $a$ | : actuator (A) |
| $c$ | : attitude control of B |
| $X,Y,Z$ | : along or about X, Y and Z axis |

## 1. Introduction

For a class of satellites, very tight pointing accuracy, such as sub-micro radian pointing stability, is often required for the primary mission instrument(s). Typical examples are astronomical satellites that observe celestial bodies using large telescopes with long focal length, [1,2)] and optical communications satellites that receive and transmit high throughput data from/to other satellites or ground stations using narrow beam laser. [3,4)]

To achieve such tight pointing requirement of the mission instrument(s) (referred to as "mission payload" or simply "payload" hereafter), however, it is usually far beyond the capability of conventional attitude control system (ACS).[1,2)] The main reasons are the presence of various internal disturbances, the limit of control bandwidth, the limit of sensor capability (e.g., resolution and noise), and thermal distortion of payload structure. In order to cope with the issues, the most popular approach might be the introduction of a payload pointing control system (PCS)[1-6)] typically using a fast steering mirror (FSM), sometimes called as a tip-tilt mirror (TTM), in combination with a vibration isolation system (VIS)[1,7,8)] between disturbance sources and the payload. A dedicated sensor that precisely detects the pointing error of the mission payload relying on some pointing reference is also a key to the PCS. For some spacecraft, the pointing error signal from the sensor is fed back directly to the ACS that is specially designed to have much wider bandwidth than an ordinary ACS, instead of using FSM. [1,5)]

In this presentation, however, an alternative approach that utilizes 6 DOF(degree of freedom) precision control of payload using 6 axis actuator, instead of PCS and VIS, is pursued. This system provides the function of PCS and VIS simultaneously. A general view of the concept is first presented, and the basic control architecture and schemes that are essential to realize the system are studied, based on simple dynamic models. The use of hybrid actuator is referred to with its unique features compared to a fully active actuator. Then fundamental properties of the system are discussed, and they are compared with those of conventional PCS plus VIS system. Finally, areas for the future work are mentioned.

## 2. Concept of the System

### 2.1. Basic concept

The core of the concept[9,10] is to dynamically disconnect the payload from the spacecraft bus. Then a set of non-contact actuators with at least 6 DOF, i.e., 3 DOF translation plus 3 DOF rotation, are configured between the payload and the bus, as is shown in Fig. 1. In order to acquire or maintain the pointing of the payload to a specific target, the actuators give forces and torques about its center of mass (CM) to the payload. At the same time, the actuators give the same forces in the opposite direction at the opposite end of the actuators as reaction forces. These forces give forces and torques about the CM of the bus, so that the attitude and position of the bus will be changed. In other word, the actuators give forces and torques to the payload by using the mass and the moment of inertia (MOI) of the bus as a proof mass. As for the non-contact actuators, voice coils and electro-static actuators may be used for example. If the set of actuators have more than 6 DOF's, the extra degrees of freedom can be used as redundancy. The system can also be seen as a variation of formation flight of the payload and the bus with a very close distance. Finally, in order to point the payload to any target direction, the system requires an appropriate sensor or a combination of sensors that has sufficient range, accuracy and frequency bandwidth.

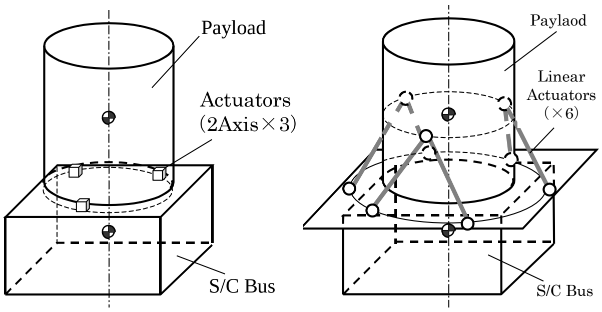



Fig. 1 Examples of 6 DOF control configuration of payload.[10]

### 2.2. Features and issues associated with the system

The most salient feature of the system would be the perfect isolation of vibration from spacecraft bus to payload. There are lots of internal disturbance sources on the bus side and their adverse effect on the payload pointing performance is often almost impossible to suppress within an allowable limit even with a wide-band powerful ACS and a very good passive VIS. The ACS has also limitation of performance in terms of ultra-fine stability that is sometimes required in demanding mission. But with this system, neither the internal disturbance on the bus side nor the ACS performance limitation affects the pointing performance of the payload at all.

There are disturbance sources as well on the payload side that affect the payload pointing. Moreover, some disturbances originated inside the bus may be transmitted to the payload through cables and coolant pipes. The payload pointing control suppresses these effects within the capability depending on its control and sensing bandwidth.

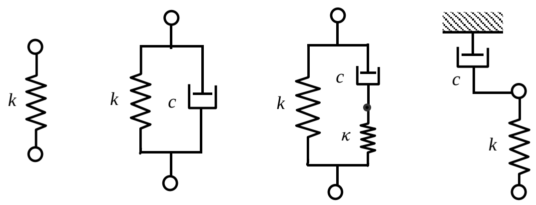
Another feature is that the system does not need any FSM or other pointing devices inside the payload, which may affect optical property or have severe impact on the optical and thermal design of the mission payload.

The use of more than 6 DOF's actuators provides not only the redundancy but also freedom in configuration to support the payload, because ordinary trusses or mounting legs that support payload does not permit more than three points of support.

There are several issues on the system: moving range, agility, control bandwidth in the presence of flexibility inside the payload, and possible fatal damage in case of failure of actuator control. In order to realize large change of pointing direction, collaborate motion with the bus is necessary to keep the relative distance between the payload and the bus within a moving range of the actuators. If agility is required, very high power will be needed to generate sufficiently large forces and torques by the actuators. To avoid the excitation of resonant modes of flexible elements of the payload, the control bandwidth of the PCS function will be limited. This might limit the suppression capability of disturbances on the payload side. And if the actuator control were in critical trouble and there were no more redundant element, then the payload motion would be completely free from the bus and be out of control. This means the fatal loss of the mission. Redundant windings and electronics of actuators and/or extra use of actuators (i.e., more than 6 DOF's) are possible measures for this failure mode.

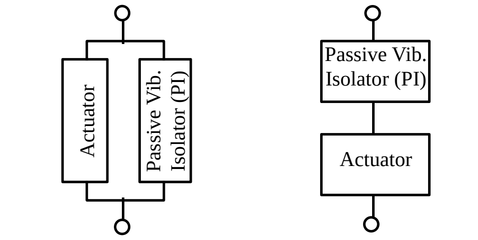
### 2.3. Use of hybrid actuator

Instead of non-contact actuators, hybrid actuators comprising of a passive isolator (PI) and an active actuator can be used to solve or at least alleviate the issues of the system stated above. Figure 2(a) through (c) shows representative types of passive isolators. Figure 2 (d) is a so-called "skyhook" type whose damper part can be realized only by active control and is shown here for reference. The hybrid actuator is constituted with one of these passive isolators and an actuator as is shown in Fig. 3. The parallel or the series configuration is selected depending on the failure mode inherent to the type of actuator. For example, a voice




(a) 1 parameter (b) 2 parameter (c) 3 parameter (d) skyhook (active)

Fig. 2 Representative types of passive isolators.




(a) Parallel configuration (b) Series configuration

Fig. 3 Configuration of hybrid actuator.

coil will be used in parallel, and a piezo-electric actuator will be in series with PI. If the active control stops to work, the voice coil will not connect both ends any more and be free in motion (open failure mode), while the piezo-electric actuator will be fixed (closed failure mode). For either case, even if the active part fails, the PI function will survive and thus the fatal error of the system can be avoided.

In normal operation, a relative position sensor such as an electro-capacitance sensor and an eddy current sensor is used to detect any small variation of distance of the spring element from the neutral position, and the sensor signal is fed back to cancel the spring force. In other word, the actuator works as a virtual spring with negative spring constant. Thus the hybrid actuator works as a non-contact actuator as a whole. It is noted that the actuator will be operated with zero power in average on orbit, because the actuator works about the neutral position of the spring. The force required for the pointing control will be added to the canceling force.

Besides a fail-safe property mentioned above, the hybrid actuator has an additional but remarkable feature that a pure active actuator does not hold, i.e., the capability of connecting the payload to the bus when it is necessary. Once the active element stops to work, the two bodies will be connected via PI. Moreover, if the active element intentionally produces a force opposite to the canceling direction of the spring, the apparent spring constant will be increased, and, as a result, the payload will be connected to the bus more tightly. This capability is thought to be specifically useful when the payload is required a large or a rapid angle change of the pointing direction. Instead of using the 6 DOF actuator power, an ordinary ACS function with reaction wheels, CMG's or thrusters can be used as actuators. This enables a large angle maneuver and agility. Among issues associated with pure active non-contact actuators, that are stated in section 2.3, only the control bandwidth issue will remain to be left.

An example of the hybrid actuator is shown in Fig. 4. It consists of a pair of simple springs (i.e., one parameter PI) and a voice coil in parallel configuration.[12)]

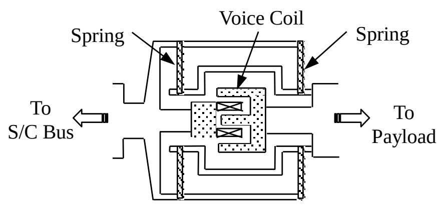



Fig. 4 An example of a hybrid actuator[12)].

## 3. Fundamental Properties of the System

### 3.1. Dynamic model of the system

Fundamental properties of the system are studied based on a simplified dynamic model combined with a few basic control schemes.

Figure 5 indicates a simplified planer motion model of the system, the definition of coordinates and related quantities. The system is modeled by two rigid bodies representing the payload (P) and the spacecraft bus (B) that are connected by a set of massless hybrid actuators. In this model, both P and B have three DOF motion, i.e., two DOF in translation (along X and Z axes, denoted by $x$ and $z$), and one DOF in rotation (about Y axis, denoted by $\theta$). Figure 6 is a further simplification of the planer model; (a) is one dimensional translation (or linear) motion model, while (b) is one dimensional rotation (or angular) motion model. Sensors, actuator and controller locations are also indicated in Fig. 6, which are omitted in Fig. 5.

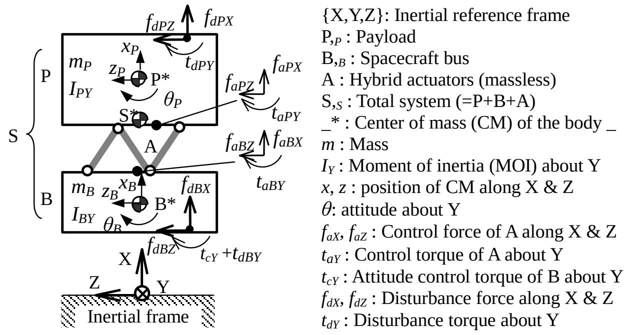
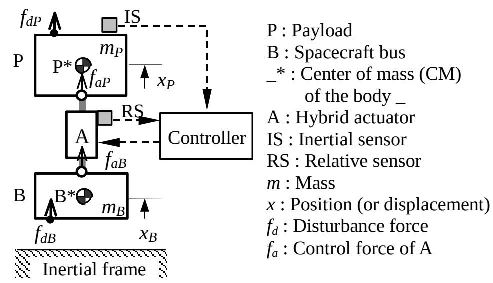
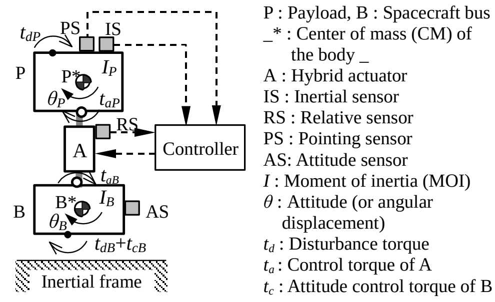



Fig. 5 Simplified planar motion model consisting of two rigid bodies.




(a) One axis translation (or linear) motion model




(b) One axis rotation (or angular) motion model

Fig. 6 Simplified one axis motion model consisting of two rigid bodies.

### 3.2. Control architecture

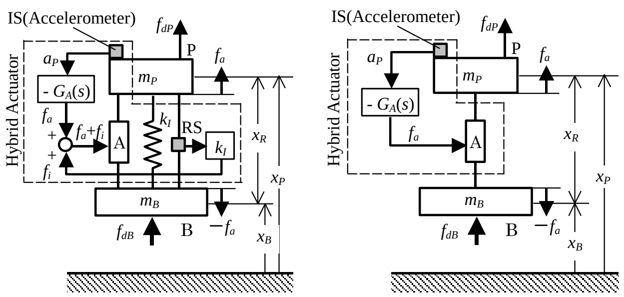
In Fig. 6(a), the relative sensor (RS) is used to cancel the spring dynamics of passive isolator (PI) inside the hybrid actuator (A). The inertial sensor (IS) attached on P, is used by the controller of A for the purpose of maintaining the P position with respect to the inertial reference frame. The position control force that is produced by A and exerts on P ($f_{aP} = f_a$), also exerts on B in the opposite direction ($f_{aB} = - f_a$). (See Fig. 7.) The reason why the position control of P is necessary even if only the attitude of P is of interest, is that both position and attitude of P must be taken care anyway as long as 6 DOF actuators are used for the purpose of perfect vibration isolation between P and B.

For IS, an accelerometer is the most probable candidate. However, as some bias component is inherently contained in any IS output signal, a position estimation filter is constituted with a certain known position as the reference. To this end, the CM position $x_S$ of the total system S(=P+B+A) can be used, because internal torques and forces generated by hybrid actuators and ACS do not affect the momentum of S, unless the thrusters are fired. The external disturbance forces may gradually change momentum of S in a long term, but the effect could be neglected in the filter because its time constant will be much longer than the filter time constant. Thus $x_S$ is treated to be constant with respect to the inertial frame, and $x_S$ can be set to be zero. The control architecture described above is expressed as a functional block diagram of Fig. 8(a).

For the rotation motion that is modeled as in Fig. 6(b), the control architecture will resemble to that of the translation control shown in Fig. 6(a) with some differences. RS is also used to cancel the passive spring dynamics. IS is similarly used for the attitude control of P. A gyro or a pair of accelerometers is a probable candidate in this case. A pointing sensor (PS) that detects the pointing direction or error of P. The PS can be utilized as the medium to long-term reference. Assuming that the PS detects the absolute direction or detects the error from a quasi-stationary target in inertial frame, the payload pointing estimation filter can be constructed with IS and PS in a much more straightforward way than the payload position estimation filter.

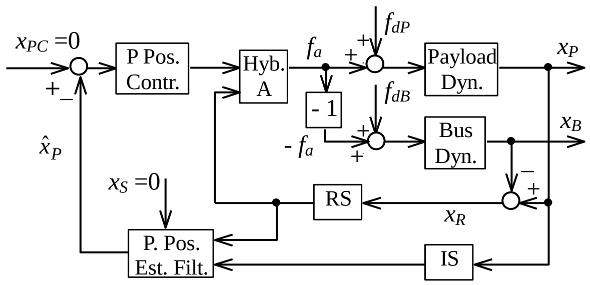
The hybrid actuator force $f_a$ exerts both on P and B in the opposite direction. But the control torques that act on P and B will not be the same in magnitude, because the moment arms are different in general. The ACS will also change the attitude of B in contrast with the translation motion of B.

The control architecture for the payload pointing control is expressed in the form of functional block diagram of Fig. 8(b).

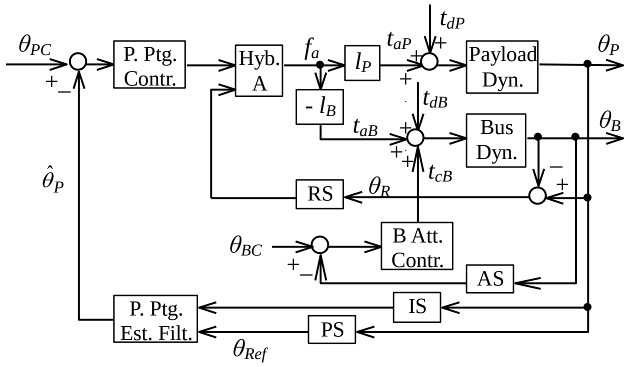



(a) payload IS plus RS feedback (b) equivalent dynamic model

Fig. 7 Inertial sensor plus relative sensor feedback with hybrid actuator.




(a) one axis translation (or linear) motion




(b) one-axis rotation (or angular) motion

Fig. 8 Functional block diagram of the system corresponding to the simplified one axis motion model of Fig. 6.

### 3.3. Basic pointing performance

Basic pointing performance of the system with fundamental PID type controller is discussed based on the one axis motion model. As one axis translation motion model is analogous to one axis rotation motion model, the translation model is used here for simplicity.

The pointing performance is measured by transmissibility from disturbance force on B or P ($f_{dB}$ or $f_{dP}$) to the payload position $x_P$. The payload position $x_P$ corresponds to the payload attitude $\theta_P$ that is equal to the payload pointing angle when the payload is modeled by a rigid body.

In the dynamic model of one axis translation motion shown in Fig. 7, two types of controllers are assumed.

$$G_A(s) = \begin{cases} c_A s + k_A & \text{; PD feedback of } x_P \\ m_A s^2 + c_A s + k_A & \text{; PD}^2 \text{ feedback of } x_P \end{cases} \quad (1)$$

where $k_A$, $c_A$ and $m_A$ are proportional, derivative and second derivative gains of the feedback control, respectively. As an accelerometer is assumed to be used for IS whose output is the acceleration $a_P$ or the second time-derivative of $x_P$, PD feedback of $x_P$ is actually I+I$^2$ feedback of $a_P$. Similarly, PD$^2$ feedback of $x_P$ is actually P+I+I$^2$ feedback of $a_P$.

Then the frequency response of $x_P$ to $f_{dB}$ or $f_{dP}$ is expressed as follows.[10)]

$$X_P(s) = 0 \cdot F_{dB}(s) + \frac{1}{m_P(s^2 + 2\varsigma_A \omega_{An} s + \omega_{An}^2)} \cdot F_{dP}(s) \quad (2)$$

; PD feedback of $x_P$

$$X_P(s) = 0 \cdot F_{dB}(s) + \frac{1}{(m_P + m_A)(s^2 + 2\varsigma'_A \omega_{An} s + \omega'^2_{An})} \cdot F_{dP}(s) \quad (3)$$

; PD$^2$ feedback of $x_P$

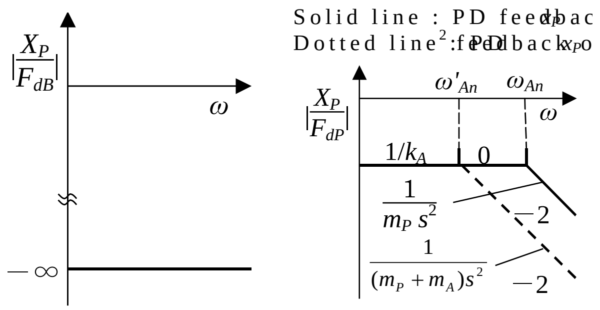
where $\omega_{An}{}^2 = k_A/m_P$, $\omega'_{An}{}^2 = k_A/(m_P + m_A)$ ($\omega_{An} > \omega'_{An}$), $c_A/k_A = 2\omega_A/\omega_{An} = 2\omega'_A/\omega'_{An}$

The transmissibility from disturbance force on B or P ($f_{dB}$ or $f_{dP}$ ) to the P position ($x_P$ ) is defined by the followings.

$$T_{dB}(\omega) = |X_P(j\omega)/F_{dB}(j\omega)| \tag{4}$$

$$T_{dP}(\omega) = |X_P(j\omega)/F_{dP}(j\omega)| \tag{5}$$

These transmissibilities are plotted in Fig. 9 with linear approximation. From the figure, it is observed that the disturbance force on B is perfectly isolated, while the disturbance force on P is suppressed up to the control bandwidth $\omega_{An}$ or $\omega'_{An}$. The control bandwidth is equal to the square root of $k_A/m_P$ , where $k_A$ is the position feedback gain and $m_P$ is the payload mass. The transmissibility from $f_{dP}$ to $x_P$ decreases in high frequency region due to a natural damping or decrease in sensitivity of $x_P$ to $f_{dP}$ by its own mass $m_P$. It is noted that the acceleration FB ($m_A$ term) is very effective in this region, because it behaves like an additional virtual mass that increases the payload actual mass $m_P$. [10] On the other hand, the acceleration FB does not affect low frequency performance. The velocity FB gain $c_A$ gives viscous damping.




(a) disturbance on the S/C bus (b) disturbance on the payload

Fig. 9 Transmissibility from disturbance input to .payload position.[10]

## 4. Further Discussions

If the system described above is compared with other related systems or concepts, the difference or resemblance will give more insights to the current system. In this context, comparison is made especially from the viewpoint of system architecture, functions and disturbance suppression capability.

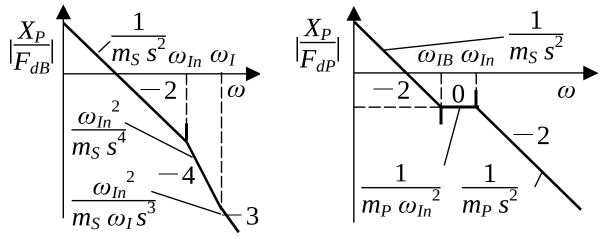
### 4.1. Comparison with passive isolators

Considering a simple one axis translation motion model again, and assuming a standard two parameter passive isolator (Fig. 2(b)) between P and B, the frequency response of $x_P$ to $f_{dB}$ and $f_{dP}$ is expressed as follows.[10]

$$X_P(s) = \frac{2\varsigma_I \omega_{In} s + \omega_{In}{}^2}{m_S s^2 (s^2 + 2\varsigma_I s\omega_{In} + \omega_{In}{}^2)} \cdot F_{dB}(s) + \frac{s^2 + 2\varsigma_{IB}\omega_{IB} s + \omega_{IB}{}^2}{m_{SP} s^2 (s^2 + 2\varsigma_I s\omega_{In} + \omega_{In}{}^2)} \cdot F_{dP}(s) \tag{6}$$

where $\omega_{In}{}^2 = k_I/m_S'$, $\omega_{IB}{}^2 = k_I/m_P = (m_S/m_P)\omega_{In}{}^2$ ($\omega_{IB} < \omega_{In}$), $m_S' = m_P\, m_B/m_S$, $m_S = m_P + m_B$, $c_I/k_I = 1/\omega_I = 2\omega_I/\omega_{In}$. $c_I$, $k_I$ are the viscous damping coefficient and the spring constant of the isolator, respectively.

The transmissibilities from disturbance force $f_{dB}$ and $f_{dP}$ to $x_P$, which are defined by Eqs. (4) and (5), are plotted in Fig. 10 using linear approximation. From the figure, it is observed that disturbance on B ($f_{dB}$) is isolated for $\omega > \omega_{In}$ , while disturbance on P ($f_{dP}$) is only damped naturally through its own mass $m_P$ or $m_S$ depending on the frequency region. Disturbance suppression is expected neither for $f_{dB}$ nor $f_{dP}$. And compariing this figure with the previous figure (Fig. 9), the functions of the proposed system are apparent: (1) perfect isolation for $f_{dB}$, in all frequency region, (2) disturbance suppression for $f_{dP}$ in low frequency region, and (3) with the P acceleration ($a_P$) feedback of the gain $m_A$, disturbance suppression for $f_{dP}$ in high frequency region also.




(a) disturbance on the S/C bus (b) disturbance on the payload

Fig. 10 Transmissibility from disturbance input to .payload position.[10]
(Passive isolator, $\omega_{In} \leq \omega_I$ )

### 4.2 Relationship with inertial stabilization system

The concept of P position feedback using inertial sensor (IS) on P is essentially same with that of inertial stabilization system in stable platform realization. One difference is that this type of stabilization system does not use RS. The other type dubbed strap-down system, in which IS is put on B and P is driven so as to cancel the movement of B using A between P and B, needs RS, though. If pointing of P to a certain target is required, the addition of pointing control loop outside the normal inertial stabilization loop using an appropriate PS on P, is also widely known.[13] The standard architecture of inertial stabilization system with pointing capability can be applied to the rotation motion control of P. This leads to an alternative architecture shown in Fig. 11, instead of the one shown in Fig. 8(b). The architecture is particularly useful when the target is moving and the PS tracks the target without knowing the absolute direction in the inertial fixed or quasi-fixed frame. In this situation, PS cannot be a reference for the estimation filter in which the IS bias or drift is to be estimated and compensated. The system of Fig. 11, however, uses IS only for short-term reference, so that IS bias or drift does not need to be estimated. Instead, PS must have sufficiently wide frequency response to track the target solely with pointing control loop. Conversely, the architecture shown in Fig. 8(b) is suitable for the mission that requires very stable tracking of stationery target.

If the RS feedback is omitted like the inertial stabilization system of stable platform type, passive isolator dynamics are not cancelled out and are kept intact. This system still works for both translation and rotation motion, although the perfect disturbance isolation property for $f_{dB}$ (Fig. 9(a)) is lost. A special case is a simple velocity feedback of $x_P$ as is shown in Fig. 12, which is essentially equivalent to a skyhook isolator shown in Fig. 2(d). The use of force sensor between P and A, instead of IS on P, is studied in Ref. 11). Another observation is that, if the RS feedback fails to perfectly cancel the passive isolator dynamics due to a small error in feedback gain, for instance, the inner RS feedback loop might become weakly unstable. But the whole system will still remain stable by way of outer IS (and PS) loop.

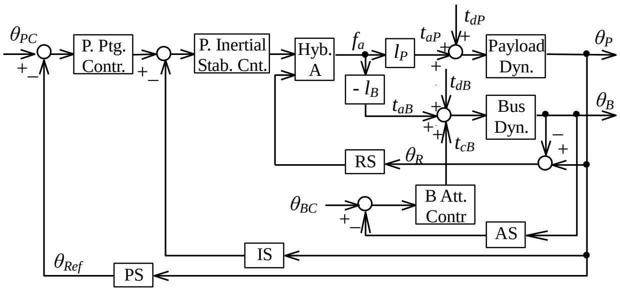



Fig. 11 Alternative functional block diagram of the one-axis translation system

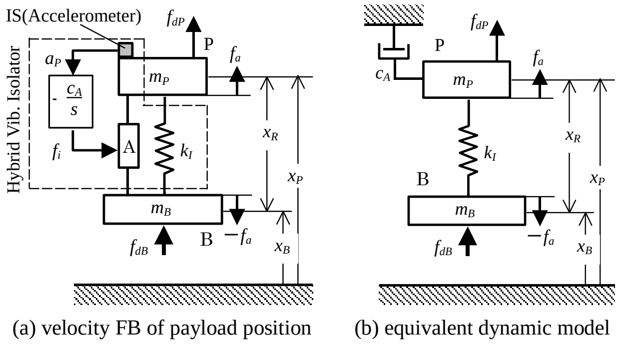



Fig. 12 Inertial sensor velocity feedback with hybrid actuator

### 4.3. Preceding studies with many similarities

Besides various types of passive vibration isolators, active and hybrid isolators have been widely studied as well. Most of them intend to improve isolation performance, namely, the extension of isolation region to a very low frequency, decrease of resonant peak levels without deteriorating the isolation performance, improvement of performance in high frequency region including the avoidance or suppression of multiple resonant peaks and surging effect of springs, etc. Some of them go toward the addition of pointing capability. Above all, the one shown in Ref. 8) named as IPS is pretty close in terms of hardware architecture to the system studied in this paper. A difference is that, besides RS and IS, IPS furnishes with a load cell at the P side end. But its concept seems to be slightly different; it is a hybrid system consisting of a passive isolator (PI) and an actuator (A) that can steer the orientation of P. Inertial stabilization of P is also intended. But the cancellation of PI dynamics with RS does not seem to be attempted. Moreover, there are no remarks on P position control such as one stated in Fig. 8(a).

A system named DPF presented in Ref. 9) is much closer in concept to the system discussed in this paper. However, the DPF adopts purely active actuators (i.e., voice coils) without any PI inside. And active P position control schemes are not mentioned, either, in any other DPF related papers.

Therefore, the schemes for P position control would be an area for future work.

## 5. Conclusion

Concept of 6 degree-of-freedom (DOF) precision control of payload, which utilizes 6 axis hybrid actuators between the payload and the spacecraft bus, is presented. This type of control system is thought to be especially suitable for the payload that requires very demanding pointing accuracy, such as a space telescope. The system concept is stated and then some fundamental properties of the system are derived based on a simple two rigid-body dynamic model with basic control schemes. The advantages of the use of hybrid actuators instead of pure active actuators are also discussed.

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