Intrinsic Placing Behavior in Zero-Power Controlled Magnetic Levitation Object Handling*

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***Abstract*— This paper introduces an aspect of Zero-Power magnetic levitation control, in which the levitated object is released or placed in a natural way without any external control commands. This intrinsic placing behavior is a result of the characteristic control feature that the coil current is actively controlled to zero instead of controlling the air gap, which is the case in conventional control strategies. The principle of this placing behavior will be explained and analyzed in this paper. A guideline to tune the controller settings to achieve this placing behavior is given and it will be supported by experiments.**

***Index Terms*— Zero-Power Magnetic Levitation, Non-Contact Object Handling, Pick and Place**

I. INTRODUCTION

Zero-Power (ZP)-control [1] is attractive for magnetic levitation (MagLev) applications as virtually no power is consumed when the system is at steady state. Typically, a permanent magnet provides a bias flux in the magnetic circuit, such that an equilibrium between the attractive force of the magnet and the load force exists, which does not require any external effort. The advantages of low power consumption and low heat generation has proven this control strategy to be valuable in space applications [2][3] and clean room applications [4]. The unique characteristic that the levitation system behaves as if it has a negative stiffness can be used in vibration isolation systems to achieve high stiffness against direct disturbances without worsening the performance in reducing vibrations transmitted from the ground [5].

Magnetic levitation is also used in object handling tasks, such as micro-automation [6] or Pick and Place [7]. For Pick and Place, ZP-control can be beneficial as it allows to levitate objects with different masses while maintaining low power consumption. Handling an object with levitation techniques in a Pick and Place task, as shown in Fig. 1, has the main advantage that there is no mechanical contact between the tool and the object. The intrinsic placing behavior using zero-power control and magnetic levitation is first mentioned and used in [7] as an alternative way to release the object. Due to the zero-power controller, the object can be released by making contact at the desired location and temporarily forcing a smaller air gap. By moving the electromagnet away from the object again, placing can be realized. One of the main advantages of this intrinsic placing behavior is that it is very simple and does not require any external commands to realize it. For PD-control for example, a switch or releasing script would be necessary to achieve placing, but with ZP-control the object will be automatically released due to the motion profile the object makes. This simple method can reduce the complexity and cost of such a object handling tool.

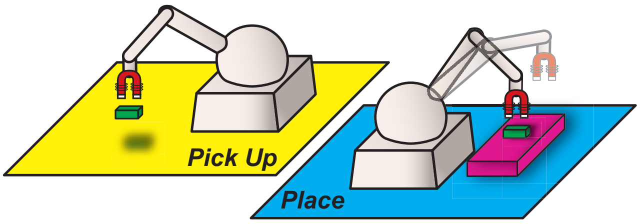

Fig. 1. Pick and Place task with Magnetic Levitation

In this paper, that placing behavior is further analyzed and its working principle is given. In section II, the model for magnetic levitation, used in this paper is described and details of ZP-control are given. The principle of placing is explained in detail in section III. Section IV gives a guideline to realize the placing behavior. Experiments verifying the theoretical results are shown in section V. Section VI is the conclusion.

II. MODEL

A. Equation of motion

The linear equation of a single-degree-of-freedom magnetic levitation system is well known. Fig. 2 shows a hybrid electromechanical levitation system, consisting of a pure electromagnet and a permanent magnet. The attractive magnetic force $\tilde{F}_{EM}$ is a nonlinear function of the air gap $\tilde{z}$ and the current $\tilde{i}$. The force is linearized in the operating point $i_0 = 0$, $z_0 = \tilde{z}_e$ and $F_0 = F_g$), where $\tilde{z}_e$ is the air gap for which the operating force is equal to the load force, typically the gravitational force F_g. By introducing deviations from the operating point as i, z, F_{EM}, shown in Fig. 2, the linear force equation is

$$m\ddot{z}\left(t\right) = k_i i\left(t\right) + k_s z\left(t\right), \tag{1}$$

where m is the mass of the levitated object, k_i is the force-current factor and k_s is the force-displacement factor. For

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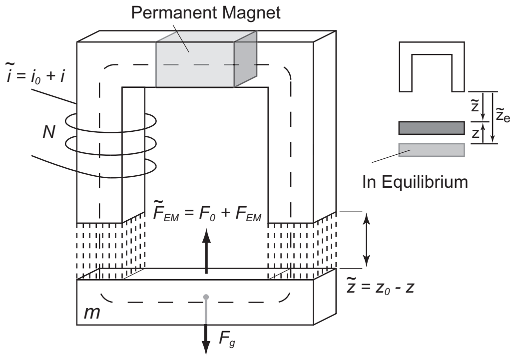


Fig. 2. Hybrid Electromagnet

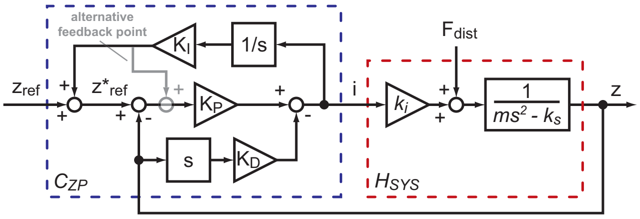


Fig. 3. Zero-Power control by integral feedback of current

simplification, the magnetic levitation is assumed quasi-static and effects such as saturation, heat loss and leakage flux are not considered.

For current-controlled MagLev systems, the transfer function of this system H_{SYS}, is derived from (1) in the Laplace domain, where each variable is capitalized and initial conditions are assumed to be zero:

$$H_{SYS} = \frac{Z(s)}{I(s)} = \frac{k_i}{ms^2 - k_s}. \tag{2}$$

The system is inherent unstable, as it has one pole in the right-half-plane (RHP) and active control is necessary for stable levitation.

B. Zero-Power Control

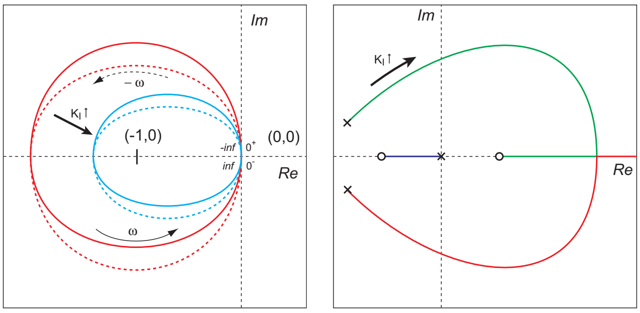
Zero Power Control for magnetic levitation systems can be achieved in several ways [8]. An intuitive way to realize ZP-control is to modify an existing controller with an additional integral feedback loop [4]. If a conventional ideal serial Proportional Derivative (PD)-controller is considered,

$$C_{PD} = K_P + K_D s, \tag{3}$$

an integral feedback loop can be added as shown in Fig. 3. The transfer function of this zero-power controller is

$$C_{ZP} = \frac{s(K_P + K_D s)}{(1 - K_I K_D)s - K_I K_P}. \tag{4}$$

In Fig. 3, the integral current is fed back to the reference signal z_{ref} to modify it into z^*_{ref}, which will facilitate explaining the behavior of ZP-control. This modified reference position z^*_{ref} can be considered as a varying set point, which the PD-controller will try to follow. However, the integral feedback loop could also be added after the position feedback loop (Fig. 3, alternative feedback point) or even



(a) Nyquist-plot (b) Root-locus-plot

Fig. 4. Stability for increasing integral gain K_I

after the PD-controller, in which case the coefficients of (4) change, but the behavior remains the same. The transfer function with integral feedback after the position feedback would be

$$C_{PD} = \frac{s(K_P + K_D s)}{s - K_I K_P} \tag{5}$$

and is simpler than (4). Since in practice, the term $(1 - K_I K_D) \approx 1$ due to small values of K_I and K_D, (4) and (5) can be considered equal and (5) will be used for onward calculations.

The integral gain parameter K_I is a measure for the speed with which the current i will converge to zero in steady state. Tuning K_I will be the main factor in achieving placing behavior and it is discussed in the guideline. High values of K_I are unwanted as the stability of the levitation system could be compromised. This is shown in Fig. 4 by both a open loop Nyquist-plot and a Root-locus-plot of the closed loop poles as a function of K_I. In practice however, such high values of K_I are not necessary and stability problems due to high K_I values, will not occur.

For ZP-control, the reference position z_{ref} can be set to zero, even if the exact equilibrium air gap is unknown, since for steady state, the reference position will be modified (z^*_{ref}) by the integral feedback loop such that the air gap $\tilde{z}$ will automatically become equal to the equilibrium air gap $\tilde{z}_e$. Therefore, it is also not required to change the reference input z_{ref} when the weight of the levitated object is changed.

C. Behavior of ZP-control

The control strategy of controlling the current rather than the air gap is simulated in Fig. 5 by comparing step responses of PD-controlled levitation with ZP-controlled levitation. A step on the reference input will not be followed by ZP-control and the steady state will become zero again. A disturbance step, which is in this case a load reduction, will reduce the air gap at first, but for ZP-control the air gap will increase steadily until the new equilibrium between load and attractive force is reached. This characteristic is also known as a negative stiffness.

III. PRINCIPLE OF PLACING

A natural way to place a levitated object is to release it after it makes contact with the desired placing location. In

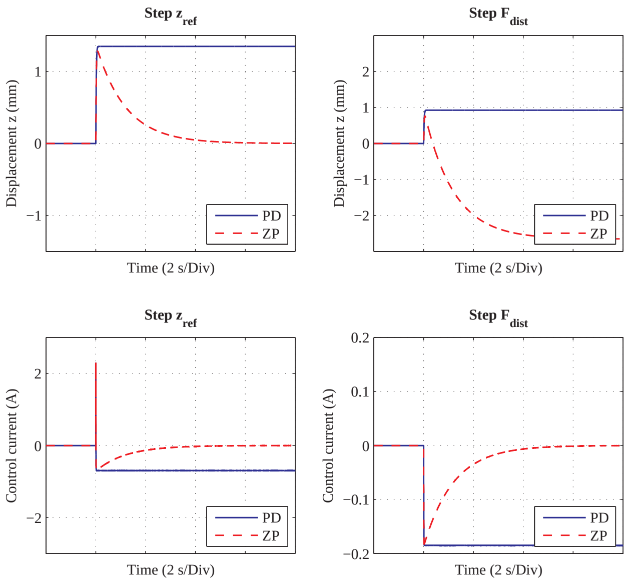


Fig. 5. Simulated step responses of displacement and disturbance force

practice this means that the air gap is reduced by the contact and a position error occurs. This position error can be used to initiate the release of the object and the electromagnet can be moved away from the levitated object, which will remain on the placing location. This is exactly how the placing behavior with ZP-control is realized.

For simplicity in reasoning the ideal situation, where $z = 0$, $(\tilde{z} = \tilde{z}_e)$ is assumed as the initial condition in the following explanation. In the case of Zero-Power control, when the air gap $\tilde{z}$ is forced to be smaller by a constant displacement d, the modified reference position z^*_{ref} will increase exponentially with time (in negative sign) and the controller will make an effort to bring the object to this bigger air gap $(z < 0)$, which can not be realized due to the contact. Since it also takes time to reduce this effort if the forced position error is relieved, the levitated object is forced to a larger air gap even when it reaches its equilibrium position. By moving the electromagnet away from the levitated object, the air gap will indeed increase. If z^*_{ref} is still relatively big when the object reaches the maximum air gap, from which it can be levitated, it can be released from the electromagnet and placing is successful.

The forces on the object are important for the release of the object and Fig. 6 shows how the attractive magnetic force relates to the air gap in case of a static measurement for both no control and active PD control, which can also be used as an interpretation for ZP-control. Here, the maximum absolute current is limited and consequently, the linear controllable region is clearly visible. The number of equilibrium positions has increased from one $(\tilde{z}_e)$ to three for active control, although two of them $(\tilde{z}^*_{e1}, \tilde{z}^*_{e2})$ are unstable. For placing, the second unstable equilibrium point $(\tilde{z}^*_{e2})$ is most important as it is the maximum air gap from which levitation is possible.

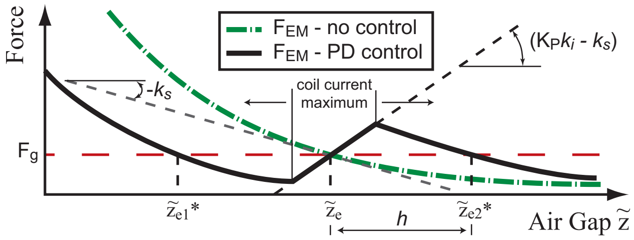


Fig. 6. Static force-air gap relationship with and without active control

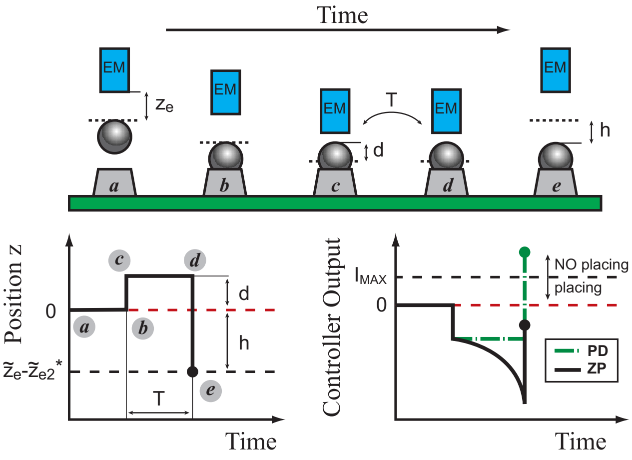


Fig. 7. Motion profile and its resulting air gap and controller behavior

The result of the placing motion on the position z is simplified shown in Fig. 7. First, both the levitation device and the object move down while z remains zero (a). Then, the object makes contact (b) and a smaller air gap is forced (c). After some time T, the levitation device is moved up again (d) and the air gap increases until it reaches (e) the critical air gap $\tilde{z} = \tilde{z}^*_{e2}$ $(z = \tilde{z}_e - \tilde{z}^*_{e2})$. From this point, the object will either remain on the platform and placing is successful, or it will be levitated again and return to its equilibrium position. Which will occur depends on the controller output at this position $z = \tilde{z}_e - \tilde{z}^*_{e2}$.

As the current reaches its limitation I_{MAX}, before the air gap is increased to $\tilde{z}^*_{e2}$, like shown in Fig. 6, it defines the critical value for the controller output in the case of placing. If the controller output is lower than I_{MAX} at $z = \tilde{z}_e - \tilde{z}^*_{e2}$, the attractive force is not strong enough to levitate the object again and placing has been achieved. If the controller output is higher, the current is maximum and the attractive force can still levitate the object again.

The controller output is a result of both the motion profile that the object follows and the controller settings with its differential equation. In Fig. 7, the controller output is also shown, where for ZP-control the controller output grows exponentially during time T, whereas for PD-control it remains constant. The differential equation (5) for calculating the controller output will become

$$\frac{K_P s}{s - K_I K_P} \tag{6}$$

if the differentiating action is neglected. With the ideal motion profile, shown in Fig. 7, the controller output at (e) can be solved for using (6) and the inverse Laplace transformation:

$$C_{OUT}(K_I, d, T) = -K_P d e^{(K_I K_P T)} + (h + d)K_P, \quad (7)$$

where d is the forced displacement error, h is defined as the difference $\tilde{z}^*_{e2} - \tilde{z}_e$ and T is the contact time. Only K_I, d and T are considered varying parameters for placing, since K_P will be set for normal stable levitation and h is characteristic for the given PD-tuned levitation system. With (7), placing will take place as

$$C_{OUT}(K_I, d, T)\Big|_{z=\tilde{z}_e - \tilde{z}^*_{e2}} < I_{MAX}. \quad (8)$$

Even though inequality (8) will not hold for PD-control ($K_I = 0$), it is interesting to note that placing could still take place with PD-control if the ideal motion profile shown in Fig. 7 could be realized. With infinite upwards speed, the object would not be able to follow this motion due to its inertia and placing could also be achieved. However, such high speeds are more difficult to realize and less practical than placing with ZP-control.

IV. GUIDELINE

Although there are three varying parameters defined in the previous section, tuning only integral gain K_I for a fixed motion profile is most attractive to realize placing. So, the following guideline is written for this purpose, but it can easily be modified for a different varying parameter. It assumes a given motion profile and only K_I is the varying parameter. The calculation will give a threshold value of K_I for which placing will occur.
Solving $C_{OUT} = I_{MAX}$ for K_I using (7), yields

$$K_I = \frac{\ln\left(\frac{I_{MAX} - (h+d)K_P}{-K_P d}\right)}{K_P T}. \quad (9)$$

With (9), a good indication for K_I can be found. However, the motion profile is an ideal one, because of the assumption of step motions. The real value for K_I will be slightly different as will be discussed in the experimental section.

In order to use this feature of intrinsic placing using ZP-control, a guideline can be abstracted from the placing principle to realize placing behavior:

1) Tune controller parameters K_P and K_D as normal PD-tuning to achieve desired stable levitation. K_I is set to zero.
2) Determine the force-air gap relationship by a static measurement with active control
3) Derive parameter h from this measurement and also note I_{MAX}
4) Estimate the motion profile parameters T and d
5) Calculate the estimated value of K_I using (9)
6) Verify successful placing and necessarily adjust K_I

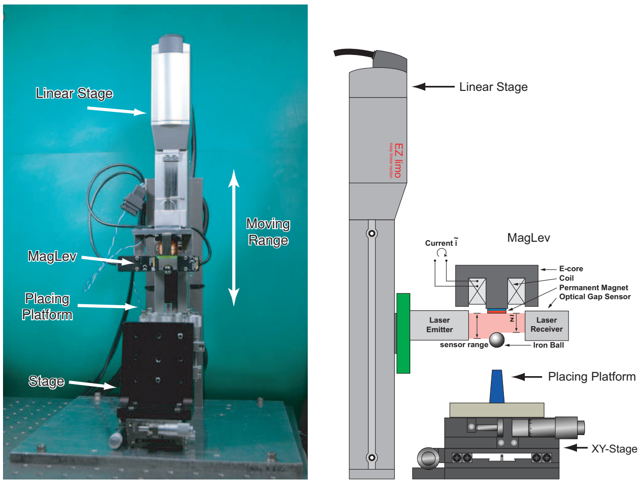
As mentioned, this guideline can be also written for the other two varying parameters, in which case the equations are

$$d = \frac{I_{MAX} h K_P}{-K_P e^{(K_I K_P T)} + K_P} \quad (10)$$

for varying the forced displacement error and

$$T = \frac{\ln\left(\frac{I_{MAX} - (h+d)K_P}{-K_P d}\right)}{K_P K_I} \quad (11)$$

when only the contact time is considered.



(a) (b)

Fig. 8. Details of magnetic levitation device on the linear stage

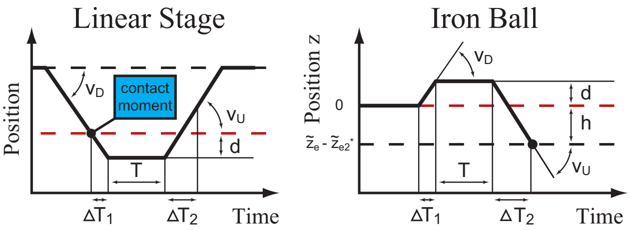


Fig. 9. Details of the motion profile used in the experiment

V. EXPERIMENTAL WORK

A. Experimental Setup

A MagLev system is attached to a linear stage (EZ limo, EZS3) to generate a controlled placing motion as can be seen in Fig. 8. The magnetic levitation device itself, consists of a hybrid electromechanical system and the details are given in Fig. 8(b). The pure electromagnet has 530 windings in an E-core and a permanent magnet (type Nd-B-Fe) is attached to the central leg. The air gap $\tilde{z}$ between the electromagnet and the object is sensed by an optical parallel beam linear sensor (Z4LB-S10V2, Omron). The absolute maximum coil current is limited at $I_{MAX} = 1.2$ A to prevent overheating the coil.

The Levitation controller is implemented in a digital signal processing (DSP) system running at 3.3 kHz using Simulink, Matlab and Controldesk, dSPACE. The control settings and some characteristic values of this levitation system are given in Table I. The controller output is connected to a power amplifier which generates the current driving the coil. A motion profile (Fig. 9), in which the downward speed v_D, upward speed v_U, contact time, T and amplitude of downward motion (to control d) can

TABLE I

CONTROL SETTINGS AND OTHER CHARACTERISTICS

Proportional gain	K_P	$2.0 \cdot 10^3$ A/m
Derivative gain	K_D	27.5 (A· s)/m
Integral gain	K_I	$1.14 \cdot 10^{-3}$ m/(A· s)
Force-current relation	k_i	$6.2 \cdot 10^{-2}$ N/A
Force-air gap relation	k_s	-32 N/m
MagLev stiffness	k_{MagLev}	92 N/m
Error when $\tilde{z} = \tilde{z}^*_{e2}$	h	2.15 mm

TABLE II

RESULTS OF PLACING EXPERIMENT, THRESHOLD VALUES

Varying Parameter[a]		Measured	Calculated
K_I	$d = 0.43$ and $T = 0.5$	**1.48**	**1.53**
	$d = 0.42$ and $T = 0.3$	2.38	2.58
d	$K_I = 1.14$ and $T = 0.5$	**0.8**	**0.73**
	$K_I = 0.80$ and $T = 0.3$	1.9	2.52
T	$K_I = 1.14$ and $d = 0.44$	**0.65**	**0.66**
	$K_I = 1.14$ and $d = 0.96$	0.39	0.42

[a] K_I in $\cdot 10^{-3}$ m/(A· s), d in mm and T in s

be regulated, is sent to the linear stage. This profile runs on the same DSP system as the levitation controller. In this experiment, both the downward speed and the upward speed are set to 30 mm/s.

The placing behavior is analyzed by separately varying the placing parameters as follows:

1) Vary the integral gain K_I; d and T constant
2) Vary the position error d; K_I and T constant
3) Vary the contact time T; K_I and d constant

Each parameter is set to zero in the initial trial and it is gradually increased until placing is achieved. A theoretical value can be calculated using the equations derived in the previous section for comparison.

B. Experimental Results

An overview of the result of the three experiments is given in Table II. It shows both the threshold values, observed from the measurement, as well as the calculated threshold values for which placing should occur. In all cases, the measured values are in the vicinity of the calculated values, indicating that the calculation method is useful for an estimate of the placing parameter.

However, one reason for discrepancies, is the assumption of pure step functions for the motion profile used in the calculation. In the motion profile used for the linear stage (Fig. 9), there is some time ΔT_1 between the contact moment and the starting point of time T, and also some time ΔT_2 after time T, which both are considered zero in calculations. In fact, during these small time intervals, the controller output also changes and the calculated parameters will always show higher values than the measured ones. The error increases as these ΔT's become relatively larger, as can be seen for instance in Table II when T is reduced from 0.5 s to 0.3 s. If more accurate results are required, mathematical software can solve the differential equation for the controller output with the motion profile as shown in Fig. 9 as input. However, due to the simplicity of the derived equations and the good indication they provide, this is not considered to be a requirement.

For each varying parameter, one of the results (**bold**, Table II) is also shown graphically in Fig. 10. In these graphs, both the air gap $\tilde{z}$ is shown, as well as its control current. The solid lines are measurements with a varying parameter and the dashed line shows the motion profile used for calculation with its calculated controller output. The separation of placed and NOT placed trials at $\tilde{z}^*_{e2}$ can be clearly seen. The NOT placed trials return slowly to the equilibrium position.

VI. CONCLUSION

A new method has been introduced to achieve a natural release of a magnetically levitated objects using an intrinsic behavior of Zero-Power control. The underlying principle of this method has been described by relating the force-gap relationship with the controller output of ZP-control. A simple formula has been deduced to find for which integral gain setting K_I, placing can be achieved with a given motion profile consisting of basic step functions. A general guideline to realize this placing method is described and verified in this paper. Experiments show that even with a simple formula, nice results can be obtained, making the realization of placing behavior with ZP-control easy.

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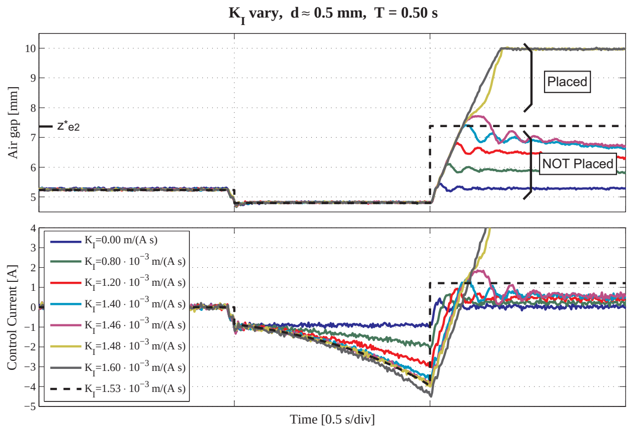
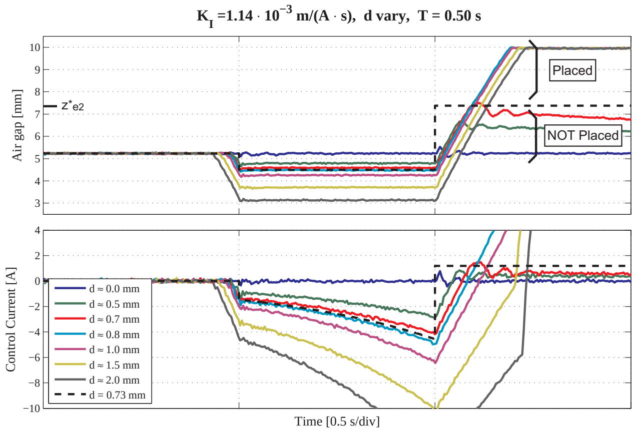
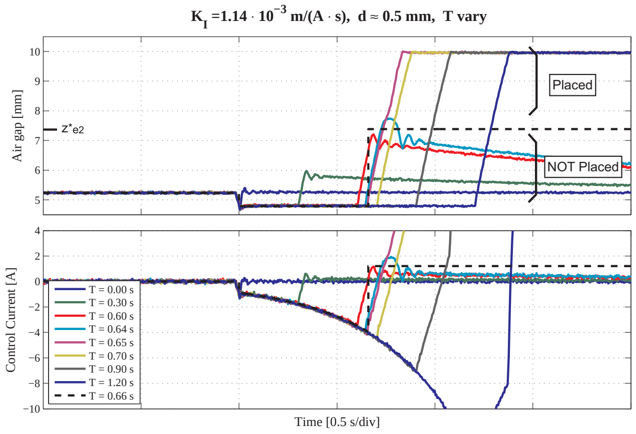

K_I vary, d ≈ 0.5 mm, T = 0.50 s

(a) Varying integral gain


$K_I = 1.14 \cdot 10^{-3}$ m/(A · s), d vary, T = 0.50 s

(b) Varying position error


$K_I = 1.14 \cdot 10^{-3}$ m/(A · s), d ≈ 0.5 mm, T vary

(c) Varying contact time

Fig. 10. Varying different parameters in placing phenomena