Electromagnet Gripping in Iron Foundry Automation Part I: Principles and Framework

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Abstract

Robot grippers are employed to position and retain parts in automated assembly operations. This paper presents an overview of electromagnet part handling framework in an iron foundry and an equivalent electromagnet circuit model. The manner in which this whole concept of automated gripping system operates will be discussed in this paper. The material handling system uses machine vision system coupled with conveyor motion and Ethernet communication strategy to assist the material handling system for transporting the foundry parts. The paper provides an overview of the electromagnet principles at play. The electromagnet interaction with the part is the key issue in the robust handling of this automated foundry system. This paper helps in the realization of the concept of automation in an iron foundry, in which the number of published studies is very limited.

Keywords: *Iron Foundry Automation, Electromagnet Gripper Characterestics, Handling Metalcasting*

1. Introduction

Robot grippers are used to position and retain parts in an automated assembly operation. In conventional foundry assembly, such grippers are dedicated to large volume handling of standard parts. The cost of the grippers may be as high as 20% of a robot’s cost, depending on the application and part complexity [1]. Electromagnet grippers have several advantages for handling ferrous parts over conventional impactive, ingressive or contiguitive grippers. [2,3] These grippers offer simple compact construction with no moving parts, uncomplicated energy supply, flexibility in holding complex parts and reduced number of set-ups [2]. However, their use is limited to ferrous materials (Iron, Nickel, Cobalt), electromagnet size is directly dependant on required prehension force; residual magnetism in the part when handled when using DC supplies requires the additional of a demagnetizing operation to the manufacturing process. While the choice of material limits application, and demagnetizing is a requirement, the holding force is an important unknown.

Figure 1 illustrates the working principle of an electromagnetic gripper.

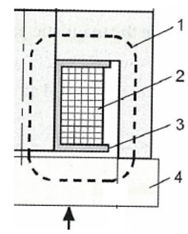

Figure 1: Principle of Electromagnetic Gripper (Adapted from Monkman, 2007)

When placed in contact with an electromagnet, the part provides a flow path for the magnetic flux that completes the magnetic circuit. The force of attraction produced by this circuit holds the part against the electromagnet. During the robot motion, the part tends to slip against the electromagnet surface if the tangential holding force in that direction exceeds the limiting force of static friction for the magnet-part contact. This component of the holding force is in turn dependent on the holding force normal to the electromagnet surface via the coefficient of static friction for the magnet-part material pair [2]. Also, the part flatness and corresponding surface roughness can have an effect on the tangential holding forces. This is important because in practical foundry operations, it is difficult to produce smooth surfaces, which are extremely flat. As a result, the source of variation in the normal holding force observed in the manufacturing plant cannot be easily explained.

Although the users of electromagnets in iron foundries know that factors such as material hardness, surface contact conditions, and electromagnet design influence the holding force, very little scientific work has been reported on this topic. Most of the available literature is of a commercial nature [4,5,6,7].The authors are aware of the gripper mechanisms available in literature [2, 8,9,10,11,12] suitable for handling iron parts, however, there is no study that would adequately clarify the mechanism by which the surface roughness affects the contact forces (normal and tangential) of an electromagnetic gripping head. Recently, Wadhwa et al. reported results from initial survey and experiments on normal and tangential holding forces by an electromagnet, but the work does not directly address the effect of surface flatness on the holding forces.

Understanding the framework for robust iron foundry prehension will save the need of time consuming costly experimentation to determine the holding forces and/or the adequacy of a given electromagnet in a gripper for assembly handling operation. Moreover, the underlying principles will help the manufacturing engineers understand the theoretical issues to be considered while selecting the electromagnets for part handling in practice and hence avoid damage to the robot and the electromagnet gripper.[8](Figure 8)

This paper presents the system configuration and a theoretical approach to modeling the holding force in magnetic grippers. The approach is termed the magnetic circuit, and utilizes Kirchoff's law for magnetic circuits. A predictive model for the normal holding force combined with the Coulomb friction model for the tangential holding force will enable the selection of optimum operating conditions needed to prevent part slip during part handling and hence avoid damage to the part or the gripper.

2. The Foundry Automation Design Concept

The automation cell was installed between the Fettling and the Assembly area in the Foundry. [14]

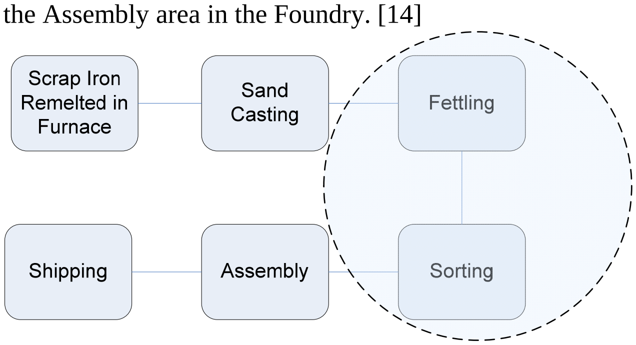

Figure 2: Metalcasting Process

The overall design concept of the Ethernet communication of the material handling system consists of three subsystems, the robot manipulator, material handling system, and the vision system as shown in Figure 5. The intelligent gripper utilized a servo mechanism in which motion controller coupled with the vision system is used for making decisions during the part handling operation.

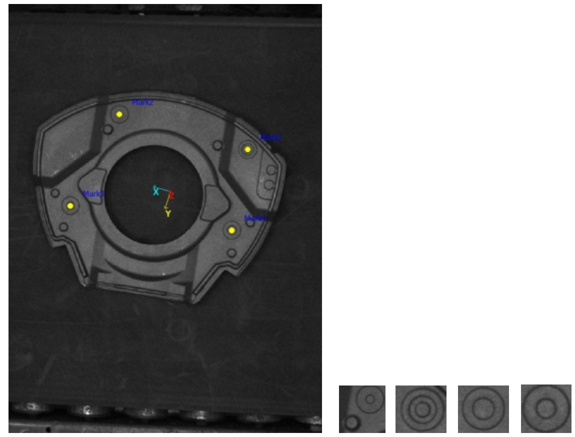

Figure 3: Markers casted on the part

The control system layout shown in Figure 4 shows the control strategy that orients the electromagnet heads according the part orientation. The purpose of the vision system was to recognize the part and extract the orientation. The second purpose of the vision system was to assist in decision making. The part orientation was identified by the markers (Figure 3) which were cast in the part. The vision system conveyed the parts orientation to the robot gripper via the Ethernet and the electromagnets were translated to orient towards the grasping regions.

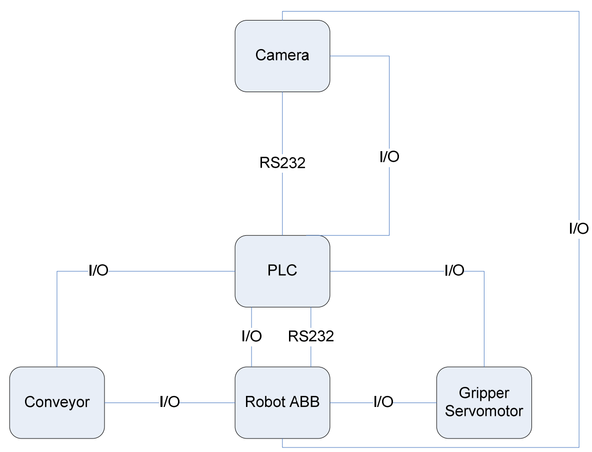

Figure 4: Schematic of Robot Assembly System

3. System Configuration

The six axis ABB ERB 6400 robot used in foundry assembly operation is shown in Figure 5. A Sony XCG-U100E overhead camera was used for identifying the orientation of the part lying on the conveyor belt, which was internally tracked by the robot. The image captured by the camera was processed by Scorpio Vision System (Tordivel AS) and transferred via closed network Ethernet connection to the Robot. The robot gripper then moved the electromagnets accordingly to pick the part.

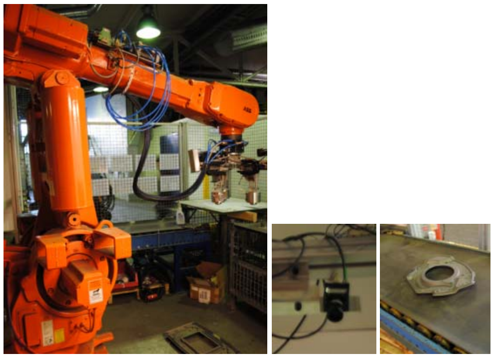

Figure 5: Robot Assembly Cell set up

Figure 6: Gripper picking part from Conveyor Belt.

The part was made of cast iron with the following nominal chemical composition: 3.2 percent Carbon, 2.65 percent Silicon, 0.45 percent Phosphorus, 0.45 percent Manganese, 0.05 percent Sulphur, 0.09 percent Chromium and 0.002 percent Lead. The surface texture of the part taken with IFM 3.1.1 is shown in Figure 7.

While the layouts provided in this paper are based on the real assembly shop data in a company, the actual production volumes and assembly station rates are not revealed due to proprietary nature of the information.

4. Magnetic Circuit Modeling

4.1 Background

The force produced by a magnetic circuit is proportional to the magnetic flux density in the circuit. The amount of flux present depends on the reluctance of the system. The reluctance is low when there is perfect contact between the part and the electromagnet surface. However, part form errors (e.g., surface errors as shown in Figure 7) and roughness lead to an imperfect contact with air gaps between the part and the electromagnet surfaces. Air is a low magnetic conductor and has a permeability (μ_0 = $4\pi.10^{-7}\,Hm^{-1}$). This results in large reluctance for elements containing air gaps that in turn can lower the holding force normal to electromagnet surface. Therefore, it is important to model and understand the effects of part flatness and surface finish on the holding forces.

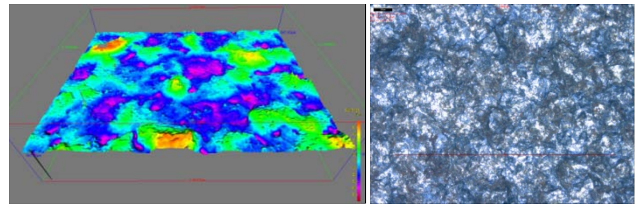

Figure 7: Cast Iron Part Surface (Obtained using IFM 3.1.1.)

4.2 The Magnetic Circuit Approach

The magnetic circuit approach is an analytical method, analogous to electric circuit analysis, for modeling electromagnetic devices [15,16]. Cherry et al. in a classic paper [17], demonstrated the duality between electric and magnetic circuits. The driving force in a magnetic circuit is the magnetomotive force (MMF) $\Im$ which produces a magnetic flux against a coil reluctance $\Re$. The reluctance is defined as:

$$\Re = \frac{l}{\mu A} \qquad (1)$$

Where l is the length of the magnetic flux path, A is the cross section area perpendicular to the flux, and μ is the permeability of the material [15].

For a given MMF and $\Re$, the flux ϕ in the circuit can be found from Kirchoff's law for magnetic circuits. The holding force can be computer using the following simple relation:

$$F = \frac{B^2 A}{2\mu_0} \qquad (2)$$

Where B represents the magnetic flux density in the airgap separating the components, A is the cross section area of the airgap and μ_0 is the permeability of air.

The flux depends on the overall reluctance of the system. The reluctance is low when there is perfect contact between the part and electromagnet. However, part form errors, e.g., roughness (Figure 7), and deviation from flatness give rise to air gaps between the part and gripper. Since actual size and distribution of the airgaps in the gripper-part interface are difficult to determine for a gripper directly in contact with the part surface; it is proposed to model a small uniform air gap that can be reproduced in an experiment. When the part rests directly on the magnet gripper surface, a uniform air gap equal to the part out-of-flatness error is could be used. It can be assumed here that the reluctance of this air gap is equivalent to the reluctance of the actual contact.

The reluctances proposed in this model include those of the electromagnet, air gaps, part, and the surrounding air medium. The procedure for modeling the reluctances is described next.

4.2.1 Electromagnet Reluctance $\Re_{Electromagnet}$. Figure 1 shows the approximate magnet geometry used to calculate the average cross sectional areas and to simplify the shape path of the flux lines. Note, only half of a cylindrical electromagnet is considered. [2] The magnetic characteristics (B-H curve) could be obtained from the supplier.

4.2.2 Part Reluctance $\Re_{Part}$. The ring-shaped part [ASTM Standards A 773A] has a non-uniform cross section perpendicular to the magnetic flux. The part reluctance is calculated using the following equation [15]:

$$\Re_{Part} = \oint \frac{dl}{\mu(l).A(l)} \qquad (3)$$

To evaluate this line integral, a numerical integration scheme can be used. The mean path is such that it is normal to the radial line representing the cross sectional area. The variation in part permeability along the flux path is explicitly accounted for in the calculation of the circuit reluctance.

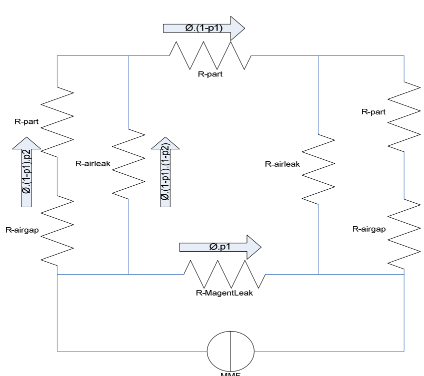

Figure 8: Equivalent Magnetic Circuit of the Magnet-Part System

4.3 Airgap Reluctance $\Re_{Airgap}$. The airgap term applies to the flux lines crossing the magnet-part interface. In reality, the airgap length varies at each point in the interface because of surface roughness and form errors. In this model, an equivalent uniform airgap length is used. The cross-sectional area of the air gap is equal to the magnet-part contact area.

Of the simplifications made above, the use of a mean magnetic flux path is most significant since it implies that the magnetic circuit model cannot predict the distribution of flux in the magnet-part system. However, it can still be used to estimate the total normal holding force and to gain an insight into the effects of magnet and part variables.

4.4 Model Solution. Solution of the magnetic circuit model involves determining the flux flowing through each component of the circuit. This is done using Kirchoff's law for magnetic circuits, which states that the sum of MMF in any closed loop must be equal to zero [15]:

$$\sum_i MMF = \Im - \sum_i R_i \phi_i = \Im - \sum_i H_i l_i = 0 \qquad (4)$$

where index i represents the i th element of the closed loop. H_i is the magnetic field in the i th element, and l_i is the length of the flux path in the i th element. For the magnet used in the gripper, the equation reduces to:

$$\Im + H_{Work} l_{Work} + (2B_{Airgap} / \mu_0) l_{Airgap} = 0$$
(5)

The factor of 2 in the last term accounts for the crossing of airgap twice, once from the N pole to the part and again from the part to the S pole. For the circuit shown in Figure 8, the part holding force is produced by the fraction of flux that crosses the magnet-part air gap, which is given by:

$$\phi_P = \phi.(1 - p_1).p_2 \qquad (6)$$

where p_1 is the fraction of ϕ leaking and p_2 is the fraction of $\phi.(1-p_1)$ entering the airgap and the part. Equation (6) when combined with Equation (2) gives the mechanical force acting on ½ of the model of the part.

5. Conclusions

Foundries, once the low relation of manufacturing engineering, are on their way to automation and undergoing investments in robot installations to increase quality and reduce costs. [7] Material handling is an important portion of foundry plant automation and if not carefully considered, can lead to rapid wear (Figure 9) and high maintenance costs for the robot interface with the part.

The part texture attributes (surface roughness and texture) affect the holding forces of an electromagnet gripper. Future effort in this area will present the effect of these attributes on normal and tangential holding forces. The results from the magnetic circuit model will be compared with available commercial software and substantiated with experimental analysis.

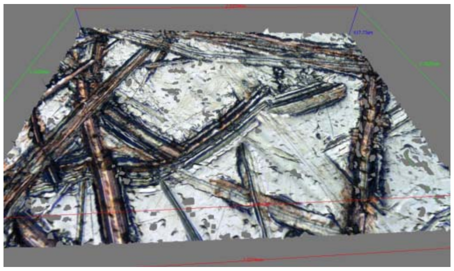

Figure 9: Scratched Electromagnet Surface. (Obtained using IFM 3.1.1.)

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