Chapter 1

Introduction

The inspection and repair of ladles, melting furnaces and converters, is a key issue to ensure the quality, productivity and security of the steel production process. The aim is to keep the time and costs of repair as low as possible without endangering either the quality or security of the process. Inspection has to be carried out as fast as possible to keep the productivity high and to avoid the risk of thermal cracks in the coating that occur when the temperature falls in the vessels.

The vessels in which molten steel is produced and transported are exposed to extreme thermal, mechanical and chemical stress. This leads to local erosion, corrosion and cracking of the refractory isolation materials. Failing to identify significant damage can have catastrophic consequences leading to a break out of the molten steel, flowing then without control onto the production floor. A regular replacement of the refractory material is extremely expansive, for this reason inspection and local repair of the vessels has been introduced recently. The aim is to extend the working life of the refractory coating. However with this, the average thickness of the material is reduced significantly towards the end of a cycle, increasing the risk of a vessel failure. This has led to a demand for robust and reliable inspection and repair systems.

Presently, there is an evolution taking place in the inspection and repair systems being used. Manual inspection by humans in heat protecting suits and repair with a manually held lance are still commonly used. Under the extreme environmental conditions humans can only perform for very short periods and the objectivity of the inspection is questionable. Robots for inspection and repair are used to minimize the risk to personnel and to raise the quality and effectiveness of the inspection and repair process.

This thesis proposes a new concept to combine telerobotics [1] [2] and panoramic optical servoing [3] for inspection, maintenance and repair[4]. There are many fields of application for telerobots in the hazardous operations associated with space, undersea, nuclear and other dangerous environments. Inspection and repair or refractories represents a new field for telerobots. Using a telerobot relieves the operator from the direct exposure to the hazardous environment prevailing near a ladle, converter or electric arc furnace, while leaving the final decision whether and where to repair to the operator.

Typically the structures being inspected are between 5 and 15 m in diameter and up to 15 m deep. Surface temperatures are in the range of 1100 °C to 1600 °C resulting in extremely high levels of thermal radiation.

1.1 Problem Statement

Section 1.1 introduces a of the possible application where a telerobot may be used for inspection and repair of refractories. Figure 1.1 shows the image of a 5 meter diameter ladle for transporting molten steel. The area most exposed to heat, corrosion and local erosion lies at the filling level of the molten steel. Inspection and repair is therefore assumed to be focused on this area and requires the following steps:

Figure 1.1: Ladle with a diameter of 5 meters for transporting molten steel. The ladle's surface temperature is about 1100 °C. To acquire the image the ladle has been rotated to a horizontal position.

1. Image acquisition through coordinated rotational motion by the telerobot;
2. Registration of the images using normalized phase correlation;
3. Automatic image cut and paste to set up the panorama using the narrow strips of the dense image map;
4. Mapping between the measurement position and the panoramic image when the images are stitched together;
5. Location of the defect by the operator who selects an area in the panoramic map;
6. Remapping of the selected area in the panorama to the real world position enables optical feedback;
7. Automatic repair by applying ceramic plasma sprayed on the selected area by the telerobot.

Solutions for a telerobots to be used at converters or an electric arc furnace would follow the same basic concept although the telerobots themselves would have to be modified for an electric arc furnace (EAF) or specially designed for a converter.

Chapter 2

System Concept

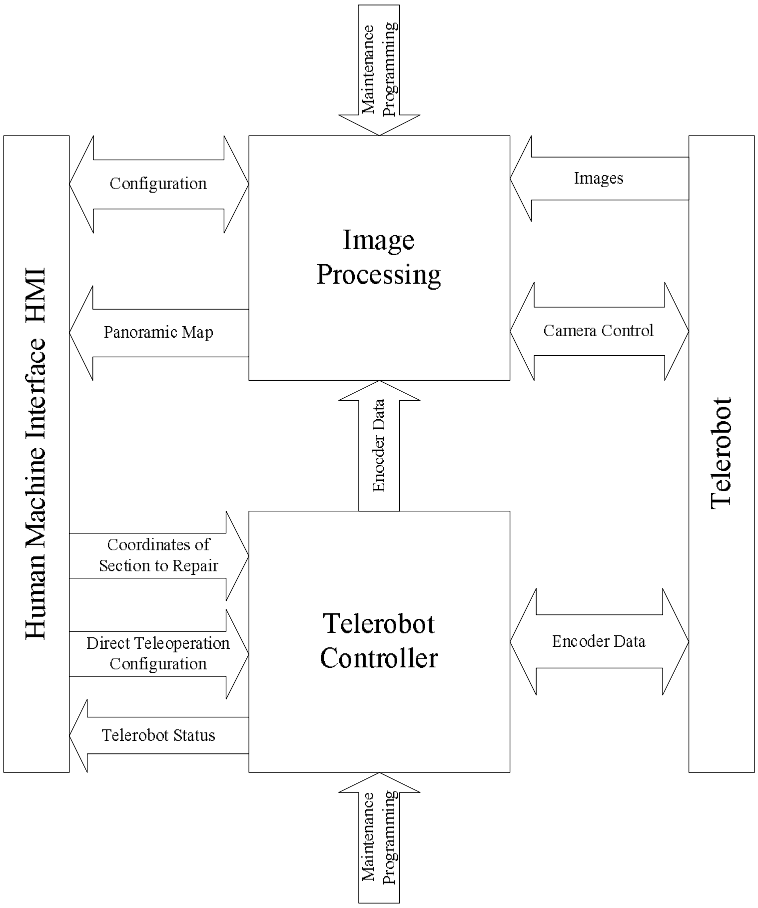

Figure 2.1: Modular system concept of the proposed combination of telerobotics and panoramic optical servoing. Both are fully automated, yet the final decision making process whether and where to repair is left to the operator. There are four main modules: 1. The Human Machine Interface (HMI), 2. The image processing module, 3. The telerobot controller, 4. The telerobot itself including the image processing hardware.

The proposed system consists of four main modules (see Figure 2.1):

1. The Human Machine Interface (HMI) (see Chapter 5.2):
   The HMI module allows the operator to interact with the telerobot:

   - Using the configuration feature: the operator can configure both the telereobot and the image processing system;
   - Using the teleoperation feature: the operator moves the telerobot manually. This can be in a case of an emergency, for maintenance of the telerobot or the image processing system, or for manual repair;
   - Using the feature of panoramic optical servoing (see Chapter 5): the operator uses the telerobot and the image processing system to automatically generate the panoramic map (see Section 5.1). After the generation of the panoramic map a defect on the surface can be located by selecting the area of the panoramic image. The telerobot will then autonomously carry out the task of repair.

2. The image processing (see Chapter 3):
   The image processing module triggers the image acquisition according to the encoder data stream provided by the controller during the coordinated motion for inspection of the telerobot which has been activated by the operator over the HMI. Furthermore it is responsible for setting up the panoramic picture. The level of projective distortion is minimized by acquiring a high density of images. Normalized phase correlation calculated via the 2D Fourier transform is used to calculate the shift between the individual images. The narrow strips from the dense image map are then stitched together to build the panorama. The mapping between the panoramic image and the positioning of the robot is established during the stitching of the images. Therefore, the panoramic picture can be seen as a map of the measured structure with fixed points at known measurement positions. This map is sent to the HMI;

3. The telerobot controller:
   This module is responsible for the control of all functions of the telerobot (movement, repair). Furthermore it provides the necessary encoder data for the image processing module and the HMI module. The encoder data stream during the inspection process is used to trigger the image acquisition;

4. The telerobot itself including the image processing hardware (see Chapter 6):
   The telerobot has to be able to carry out both the task of inspection and repair, not at the same time but sequentially. The robot itself and of course the image processing hardware have to be designed and selected to be able to endure temperatures up to 1600 °C.

The main idea behind this concept is to have a modular system which can be used to inspect and repair refractories at high temperature, as well as for other similar extensive inspection and subsequent processing operations carried out with a telerobot.

Part II

Theoretical and Practical Background

Chapter 3

Panoramic Imaging

Standard cameras have a field of view that is limited and therefore not suitable for many image processing applications that require an image of the full scene. A larger field of view may be obtained using:

- Omnidirectional vision sensors [5, 6] consisting of a single camera and special mirrors (e.g. spherical, conical, hyperboloidal, paraboidal);
- Fish-eye lenses that imbue conventional cameras to view objects within as much as a hemisphere. Images acquired using fish-eye lenses have substantial distortions;
- Mosaicing using rotating and or translating vision sensors [7, 8, 9, 10]. Traditionally a sequence of images is acquired and then stitched together to generate the panoramic image. A recently in the literature occurring new mosaicing method is the crossed-slits projection [11].

3.1 Image Registration using Normalized Phase Correlation

The shifts between the single images of one measurement run are determined using normalized phase correlation [12, 13, 14] , calculated via Fast Fourier Transform (FFT) [15, 16, 17] based algorithm. Given two images that are the same but only differing by a shift, i.e.,

$$I_2(x, y) = I_1(x - x_0, y - y_0). \tag{3.1}$$

Using the phase shift theorem the Fourier transform of each Image can be related,

$$J_2(\zeta, \eta) = e^{-j2\pi(\zeta x_0 + \eta y_0)} J_1(\zeta, \eta), \tag{3.2}$$

where the phase shift can be calculated as

$$e^{-j2\pi(\zeta x_0 + \eta y_0)} = \frac{J_1^*(\zeta, \eta) J_2(\zeta, \eta)}{|J_1^*(\zeta, \eta) J_2(\zeta, \eta)|}. \tag{3.3}$$

The desired spatial shift can be determined by applying an inverse Fourier transform and finding the location of the function maximum

$$c(\Delta x, \Delta y) = \mathcal{F}^{-1}\left[e^{-j2\pi(\zeta x_0 + \eta y_0)}\right]. \tag{3.4}$$

The location of the maximum of $c(\Delta x, \Delta y)$ is used as the shift between the images.