Transmissive Optical Pretouch Sensing for Robotic Grasping

Di Guo, Patrick Lancaster, Liang-Ting Jiang, Fuchun Sun and Joshua R. Smith

Abstract— **Robotic grasping has been hindered by the inability of robots to perceive unstructured environments. Because these environments can be complex or dynamic, it is important to obtain additional and precise sensing information just before grasping. This paper expands upon the pretouch modality by introducing a transmissive optical sensor. It can unambiguously indicate the presence or lack of objects in close proximity. A wide variety of items that other sensors fail to sense, such as extremely soft or shiny objects, can be detected by the proposed sensor. The sensor is also fully integrated into the fingertips of the PR2 robotic platform and manufactured with inexpensive, commercially-available components. Several experiments are conducted to verify its utility in both environment perception and robotic grasping. It is shown that the perception information supplied by the sensor facilitates effective robotic grasping.**

I. INTRODUCTION

Robotic grasping is still a challenge due to persistent difficulties in perceiving unstructured environments. Long range vision/depth sensors can capture geometric and positional information, but inevitable problems such as occlusion and coordinate calibration errors may result in imprecise estimation of object shape. Since grasp planning is very sensitive to the shape estimation of an object, robotic grasping informed only by vision/depth sensor data is not reliable. To improve grasp accuracy, other approaches have applied tactile sensor feedback. Although tactile sensing data can describe the geometric configuration of an object with fine resolution, the required contact between the sensor and object may displace the object. These sensors may also fail to detect compliant objects. The advent of pretouch sensing, a sensing modality with a range intermediate to that of vision/depth sensing and tactile sensing, allows for the collection of detailed geometric information without physically contacting the object of interest. Various methods [15][18] of pretouch sensing have been previously explored, and each depends on different physical properties to detect an object. None of these methods are effective on all types of materials, resulting in detection failures for certain types of objects (TABLE I).

In this paper, a transmissive optical sensor is proposed. The sensor is composed of an emitter-receiver pair. The emitter utilizes infrared emitting diodes to transmit IR light beams to photodiodes on the receiver. The sensor has been installed into the fingertips of Willow Garage's PR2 robot. Objects between the fingertips (but not necessarily touching them) will break one or more beams and be detected by the sensor. In particular, the sensor can detect both soft and/or shiny objects, which are difficult for other sensors to detect. Experiments have demonstrated the efficiency of our transmissive optical sensor in the application of both environment perception and robotic grasping. The main contributions of this work are summarized below:

- A novel transmissive optical pretouch sensor is developed and has been fully integrated into the fingertips of a PR2 robot platform and manufactured with inexpensive, commercially-available components.
- The proposed pretouch sensor can provide a simple, fast and reliable way to detect materials that previous sensors fail to detect such as shiny objects and extremely compliant materials.
- Heuristic algorithms are proposed for object detection in different situations with the proposed pretouch sensor and experiments are conducted to illustrate the efficiency of the algorithms in both environment perception and robotic grasping.

The content of the paper is organized as follows: In Section II, related work about vision/depth sensors, tactile sensors, and pretouch sensors in robotic grasping are presented; The mechanism and hardware of the proposed transmissive optical sensor are illustrated in Section III; In Section IV, the heuristic algorithms for object detection are described and corresponding experiments are conducted to verify the efficiency of the proposed pretouch sensor in different situations. Finally, in Section V, we come to several conclusions about our approach.

II. RELATED WORK

Many grasping syntheses are based on the geometry model of the object [1]. However, in real unstructured environments, it is usually impossible to know the geometry model of the object beforehand. Long range vision/depth sensors are usually used to provide the shape information of the object for robotic grasping, although they may not provide a precise model of the object due to occlusion and unavoidable sensor noise. With this in mind, various approaches [2][3][4] for robotic grasping with incomplete sensor data have been

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proposed. However, for some transparent or shiny materials, the vision/depth sensors are incapable of producing any sensor information.

Different from long range vision/depth sensors, tactile sensors are short range contact sensors that are becoming increasingly popular in the area of robotics. They can provide valuable tactile information when the robot physically interacts with the object frequently. Specifically, tactile sensors can correct occlusion and inevitable calibration errors in common visual sensors. As a result, they have been successfully applied to many problems in the field of robotics [5][6][7][8][9][10][11]. Although tactile sensors can provide rich local geometric information about the object, the physical interaction between the object and the sensors could displace or destroy the object[12]. In addition, exhaustive tactile sensor probing can result in redundant contacts and requires expensive computation.

Pretouch is a modality of sensing with a range that is between that of vision/depth sensing and tactile sensing. It provides a combination of the desirable characteristics of both vision/depth sensing and tactile sensing. Through the use of a pretouch sensor, the object's geometric information can be obtained at short range without being touched, which has been shown to improve the reliability of robotic grasping[18]. There are three primary types of pretouch sensors that have been applied to robotic manipulation, namely, electric field (EF), optical, and acoustic pretouch sensors. The EF pretouch sensor [13][14][15] is employed to perform grasping as well as object exchange between humans and robots. EF sensing is achieved by transmitting an AC signal from one electrode to another and examining how the received signal is affected by nearby objects. However, EF sensing is limited to conductive objects or materials with a high dielectric constant. Optical pretouch sensing methods are attractive because of their precision and ability to detect a wide range of materials. Maldonado et al.[16] utilize optical sensors to supplement long-range vision data with measurements of areas that are occluded from the initial sensor. Hsiao et al.[17] develop an optical sensor to measure object distance and orientation, and apply this data to a probabilistic state model to perform grasping. The operation of both of these sensors required generated light to reflect off of the object of interest's surface and be received at the sensor. A problem with this configuration is that the sensors do not accurately detect objects that are shiny or transparent. Furthermore, both sensors have a non-zero minimum sensing distance. As either of these sensors get very close to an object, the amount of light reflected back to their receiver is either not sufficient or not easily predicted. In [12][18], a novel acoustic sensor called seashell effect pretouch sensor is proposed. A cavity and microphone are built into the seashell pretouch sensor. The resonant frequency of the ambient sound spectrum will change when the finger approaches an object, thus the seashell pretouch sensor can be utilized to obtain the object's surface information. But it can not detect certain extremely soft and light materials such as tissue paper.

The proposed transmissive optical pretouch sensor is designed to unambiguously indicate the presence of objects in close proximity to the robotic fingers. In contrast to other optical pretouch sensors, its operation doesn't rely on light reflected from the surface of the object. This allows it to detect objects that other optical sensors fail to sense, such as shiny objects. Tissue paper and other thin or soft objects can also be detected by it. TABLE I lists the capabilities of current pretouch sensors for objects of different materials. It can be concluded from the table that the proposed transmissive optical sensor can detect a wide range of objects, including extremely soft objects such as tissue paper or shiny tools. In addition, the proposed sensor has already been fully integrated into the standard PR2 fingertip and is manufactured with inexpensive, commercially-available components(Fig.3). Unlike previous fixed crossbeam sensors[22] that are only suitable for a restricted set of shape geometries, our sensor can be used in more complicated environments and facilitates on-line iterative detection.

TABLE I

CAPABILITIES OF CURRENT PRETOUCH SENSORS FOR OBJECTS OF DIFFERENT MATERIALS

Object	EF sensor [15]	Optical sensor [17]	Seashell sensor [12]	Proposed sensor
Paper box	X	V	V	V
Transparent bottle	X	X	V	X
Shiny tools	V	X	V	V
Tissue paper	X	–	X	V

"X": Cannot detect; "V": Can detect; "–": Data not available.

III. The Transmissive Optical Pretouch Sensor

The motivation of the proposed pretouch sensor is to provide a simple, fast and reliable mechanism to detect objects that other sensors are unable to sense due to compliance, softness, porosity, or acoustic absorptivity issues[19]. The transmissive optical sensor was designed for use in parallel jaw grippers, which is a very popular and widely used type of robotic gripper. Each sensor consists of an emitter-receiver pair. The receiver and emitter circuitry are encased in separate 3D printed shells that measure 32 mm x 19 mm x 6.5 mm. Metal screw inserts have been melted into the plastic of the sensors case so that it can be securely fastened to the gripper of the robot. The structure of the sensor is shown in Fig.1. The emitter utilizes four infrared emitting diodes to transmit 940 nm beams of IR light to four photodiodes on the receiver. The photodiodes are pre-equipped with filters to eliminate potential noise caused by ambient light. The sensor's circuitry processes photodiode measurements and sends the results to the robot. The emitter and receiver are fully integrated into the fingertips of the PR2 such that that each infrared emitting diode is aligned with a photodiode. The photodiodes of the receiver and the infrared emitting diodes of the emitter are both oriented in a rectangular fashion. This configuration allows the sensor to simultaneously determine the presence (or lack) of an object at four different locations relative to the grippers frame. The transmitted beams of light can be received at distances in excess of 8.4 cm (the gripper width), allowing the sensor to detect objects between the fingertips when the gripper is fully open, virtually closed, or at any intermediate position. The sensor samples all four locations and compares each reading to a threshold value. A beam is only interpreted as blocked if the corresponding reading is above the threshold (Fig.4). The remainder of this section will provide further details about the sensor-gripper interface, the emitter circuit, and the receiver circuit.

In order to meet the size requirements of the fingertip sensor, the necessary sensing circuitry was implemented on a dedicated PCB, as shown in Fig.2. The design of the PCB is sufficiently flexible such that it can act as a receiver or an emitter, depending on which electrical components are soldered to it. The design utilizes an FFC-FPC connector to allow a programmer to upload firmware onto the microcontroller of the receiver through an ISP interface during the construction of the sensor. During normal operation of the sensor, a ribbon cable in the gripper of the robot is inserted into the connector, which serves as the physical conduit for SPI transfer between the robot's gripper (master) and the receiver (slave). The gripper also provides power and a common ground for the sensor through the ribbon cable.

The emitter circuit consists of four infrared diodes and four resistors to control the amount of current drawn by each diode. The diodes are always on. In a future design, a microcontroller could be added to the circuit to control the state of the diodes, facilitating new measurements that correspond to different diode configurations.

On the receiver, an ATMega168 microcontroller samples the output of the four photodiodes. The output of each photodiode is connected to a switch controlled by the microcontroller. By time multi-plexing the selected input, the output of each photodiode is passed to an op amp for filtering and amplification before being sampled by the microcontroller's 10-bit ADC. The microcontroller acts as an SPI slave, thus it transmits the sampled data when requested by the master gripper. This data is then published to a ROS topic through the EtherCAT interface.

More information about the sensor and its development can be found at `https://bitbucket.org/uwsensors/pr2_pretouch`.

IV. ALGORITHM AND EXPERIMENTS

Given the pretouch sensing data, corresponding heuristic algorithms can be applied to recover the object shape information. In this section, we will demonstrate the implementation these algorithms under different situations in real experiments.

Our experiments are realized using a PR2 robot. The proposed transmissive optical sensor is fully integrated into the robot's fingertips and a Kinect is mounted on the head of the robot to provide the raw scene point cloud. Our

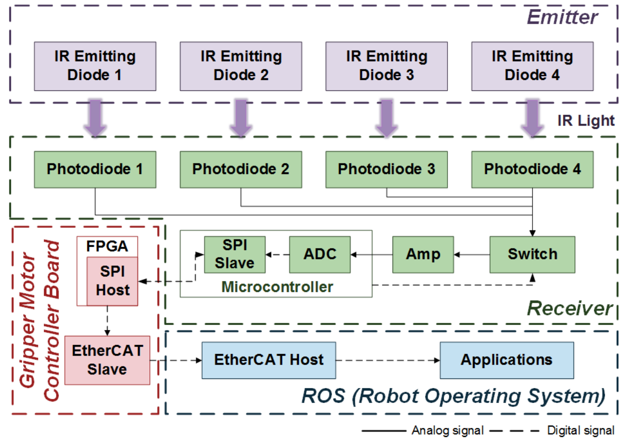

Fig. 1. The structure of the transmissive optical sensor.

Fig. 2. The transmissive optical sensor's PCB.

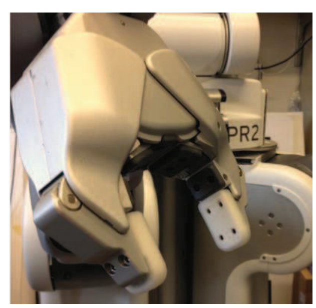

Fig. 3. The optical sensor is fully integrated into the PR2 gripper. It can detect the presence of an object at 4 locations.

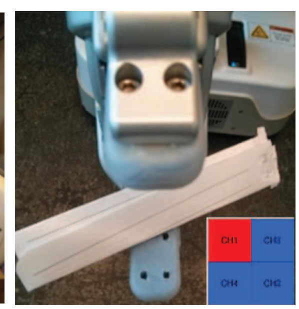

Fig. 4. A demonstration of the optical sensor's operation. A light beam is broken when there is an object between the emitter-receiver pair.

experimental results are verified in rviz, which is a 3D visualization tool for ROS (Robot Operating System).

A. *Preliminary work*

With the scene point cloud obtained from the Kinect, we first use the probabilistic framework proposed in [18] to estimate the bounding box of the object. We outline the procedure briefly in the "Shape Inference" in Fig.6. Readers can refer to [18] for further details. Fig.5 demonstrates the partial point cloud that the robot gets from the Kinect and the corresponding bounding box. The initial gripper poses in the

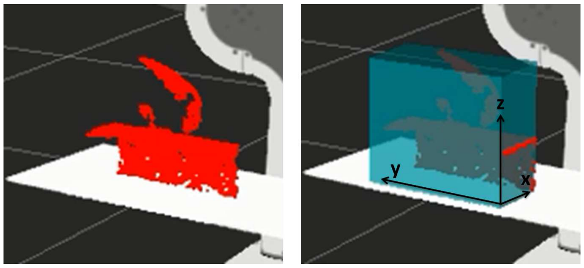

Fig. 5. Bounding box obtained from the partial point cloud.

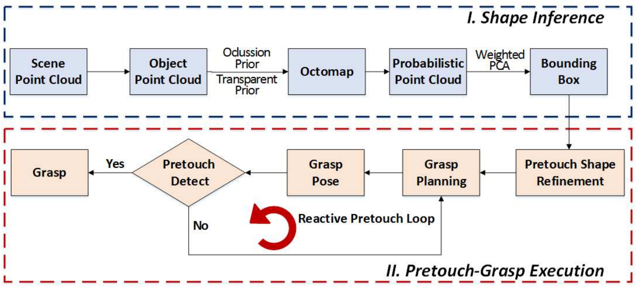

Fig. 6. The pipeline of transmissive optical pretouch sensing for robotic grasping.

following experiments are calculated based on this bounding box. The pipeline of transmissive optical pretouch sensing for robotic grasping is shown in Fig.6.

B. Algorithm 1: Edge detection for certain materials

The following experiments involve scanning objects with an edge detection algorithm that can optionally be extended to corner finding. It is particularly suitable for situations in which the point cloud of the object is extremely incomplete.

It is assumed that the gripper approaches the object from the top, the opening of the gripper is perpendicular to the y-axis of the object frame (Fig.5), and that none of the sensor's beams are broken at the initial position. Note that all vertical directions are along the z-axis of the object frame and that all horizontal directions are along the y-axis of the object frame. The algorithm is composed of the following two stages:

- Slope Determination: After reaching the initial pose, the algorithm enters the slope determination phase, in which the gripper proceeds directly downward until one or more of the beams is broken. If the movement steps are sufficiently small, this reading indicates the slope of the object's edge. From this point on, the gripper is constrained to move along the object in a single horizontal and a single vertical direction. The horizontal direction can be chosen freely, and then the vertical direction is determined by the chosen horizontal direction and the discovered slope of the object.
- Edge Tracking: We define the "edge state" as the state in which only the two bottom beams of the sensor are broken and the "corner state" as the state in which only the bottom beam opposite of the chosen horizontal direction is broken. If the sensor is in the "edge state", then the gripper is free to step in either the specified horizontal or vertical direction. Otherwise, the algorithm prescribes horizontal or vertical movements that will put the sensor in the "edge state". This proceeds until a "corner state" is found. For example, if the vertical direction is up and the horizontal direction is to the right, then the sensor has found a corner when only the lower left beam of the sensor has been broken.

1. Tissue grasping

By means of our algorithm and sensor, we can align the front side of the robot's finger to the edge of an object and trace the edge until the corner is found. The following experiment is to find the corner of a tissue and then grasp it (Fig.7). It provides a more simple, fast and reliable way for this kind of task.

Tissue paper is made of extremely soft, thin, and compliant material. Because of its unique material characteristics, it is difficult for vision/depth sensors to capture its shape information precisely, while tactile sensors are unlikely to sense such a thin object. Therefore, a delicate pretouch exploration is required before grasping. The proposed transmissive optical sensor can give accurate local geometric information about the tissue paper in real time, increasing the likelihood of a successful grasp.

The process of tissue paper grasping with the transmissive optical sensor is described in Fig.7. The upper row shows a 3D visualization in rviz and the bottom row shows the real experimental scenario in Fig.7(a-d). The markers in rviz demonstrate the pretouch sensing information gathered during the movement of the gripper. The green point indicates none of the beams of the sensor are broken, the red point means only the bottom two beams are broken("edge state") and the blue ball marks only the corner beam being broken("corner state"). The trajectory starts from the green marker. Fig.7(a) presents the point cloud obtained from the Kinect. It can be seen from the picture that the point cloud for the tissue paper is not complete. In Fig.7(b), the gripper gets to the initial position based on an oriented bounding box calculated from the initial point cloud with the weighted PCA method. The gripper tries to reach the tissue paper from the top and the pretouch detection begins. The gripper then tracks the edge of the tissue paper until it finds the corner based on the proposed algorithm (Fig.7(c-d)). The enlarged picture in Fig.7(d) demonstrates the result of edge tracking (red markers) and corner finding (blue ball). Given this precise information about the presence of the tissue paper, Fig.7(e) shows that the robot executes the grasp from the corner of the tissue paper, resulting in the tissue paper successfully being pulled out of the box.

2. Shiny object grasping

Vision/depth sensors have difficulty in detecting objects fully or partially coated in shiny material, such as spoons or hammers. This limits the accuracy with which they can perform object recognition and categorization. It is necessary to gather additional sensor information in order to complete the shape model of these objects. The proposed transmissive optical sensor is capable of detecting shiny objects, and is

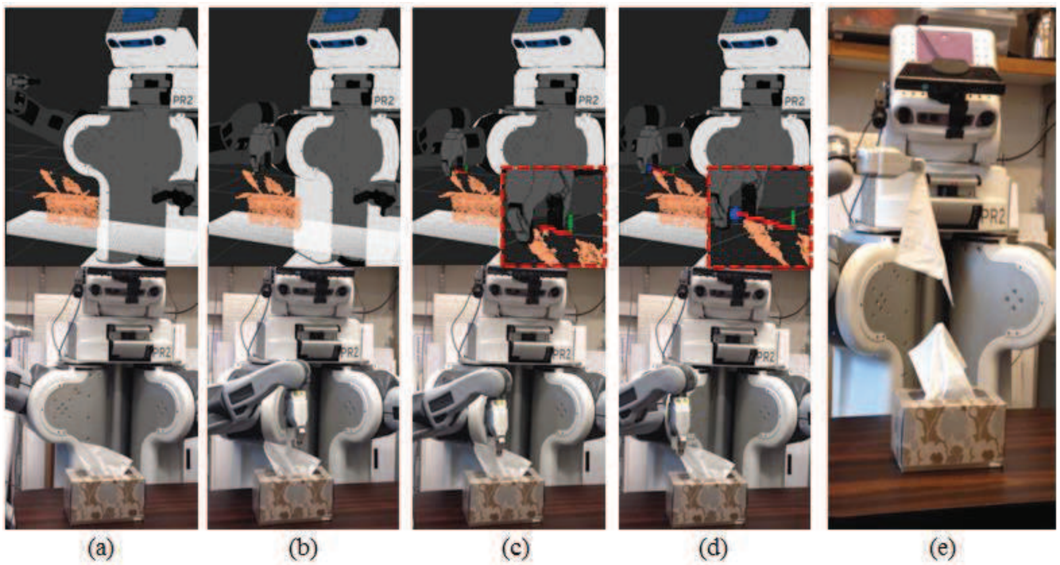

Fig. 7. Find the corner of a tissue. Fig.7(a) shows the point cloud obtained from the Kinect. The gripper gets to the initial pose in Fig.7(b). Fig.7(c-d) show that the gripper traces the edge of the tissue until a corner is found. In Fig.7(e). It can be seen that the robot successfully grasps the tissue.

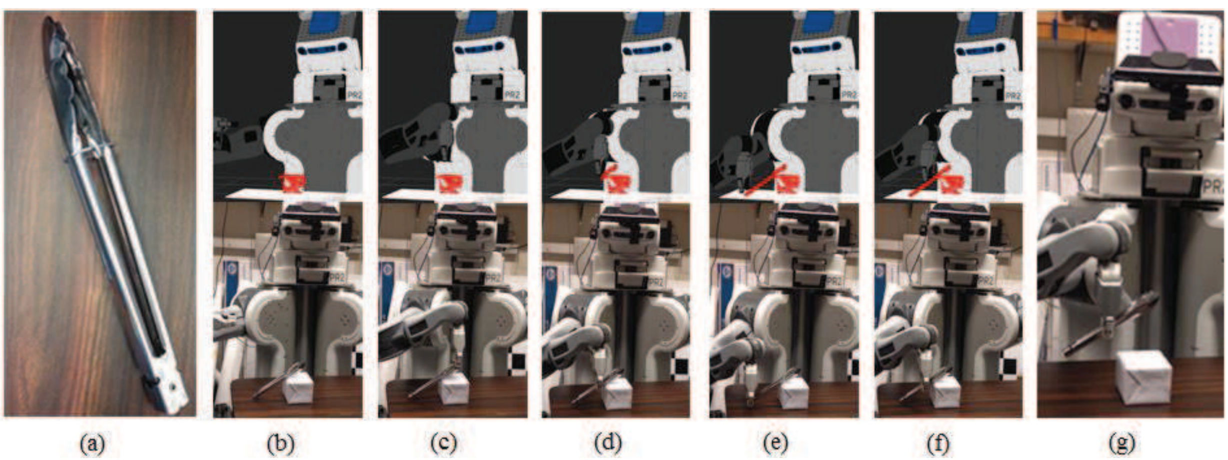

Fig. 8. Complete the shape of a shiny tong and grasp it. Fig.8(a) demonstrates the shiny tong the Kinect could not detect. Fig.8(b) shows the point cloud obtained from the Kinect. Fig.8(c-e) show the sensing result of our pretouch sensor as the gripper scans along the tong. It can be seen clearly from the 3D visualization in rviz that the shape of the tong is completed. Fig.8(f-g) demonstrates that the gripper successfully grasps the tong based on the shape information obtained from our transmissive optical sensor.

therefore able to supply this additional data.

To illustrate the effectiveness of our sensor in completing the shape of shiny objects, we try to scan a shiny tong (Fig.8(a)) placed on a tool rest, and then use collected pretouch sensing information to grasp it. Fig.8(b) shows that the Kinect can't detect the shiny tong and only provides the point cloud of the tool rest. The gripper reaches the initial pose based on the point cloud of the tool rest (Fig.8(c)). Then the gripper tries to scan the free space. When it detects the tong, it begins to scan the tong with the proposed edge tracking algorithm and completes the unseen shiny part of the tong at the same time (Fig.8(d)). The result after scanning the tong by the gripper equipped with our transmissive optical sensor is displayed in Fig.8(e). It can be seen clearly from the 3D visualization in rviz that the edge of the tong is complete. Given a complete geometry of the tong, the gripper goes to the middle of the tong and grasps it successfully (Fig.8(f-g)). The transmissive optical sensor can successfully complete the shape of a shiny object and grasp it. Note that the real size of a fully or partially shiny object can also be obtained with our transmissive optical sensor in this way.

C. Algorithm 2: center detection for small objects

Small objects, such as a glue stick, are difficult to grasp successfully from the top. It is even more difficult to perform this type of grasp with a parallel jaw gripper because any amount of positional bias can result in a poor grasp. A feasible approach to solve this problem is to firstly center the gripper on top of the object and then execute the grasp. We employ a rotation-translation scheme with our transmissive optical sensor to find the center of the object. Because the sensor contains four infrared emitting diodes oriented in a

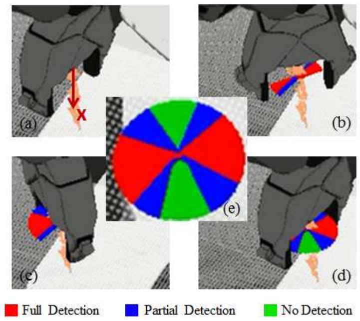

Fig. 9. The process of rotation scanning. The gripper rotates around the x-axis (in gripper frame) for 180 degrees (Fig.9(a-d)) and records the sensing information. Fig.9(e) shows the complete pretouch sensing information.

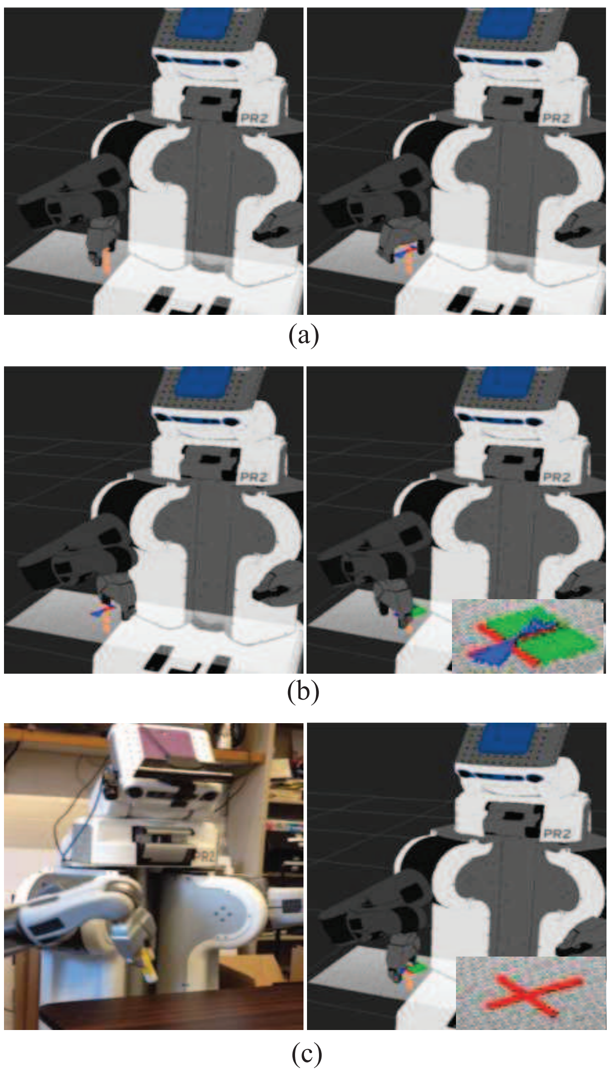

Fig. 10. Grasp the glue stick with rotation-translation scanning. Fig.10(a) and Fig.10(b) demonstrate the rotation and translation scan processes respectively. The gripper grasps the glue stick successfully in Fig.10(c).

rectangular fashion (Fig.4), we can actually get data from the four positions of the fingertips. We divided them into two groups such that the sensor was split into left and right sides. There are two stages in this scheme.

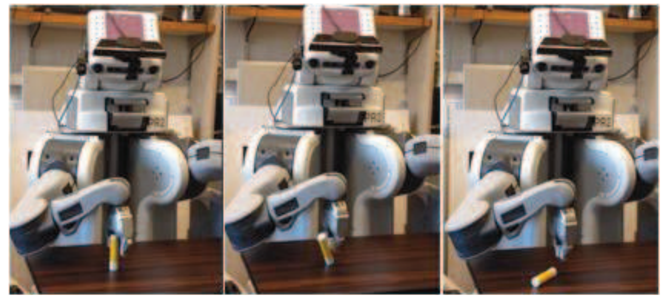

Fig. 11. A poor grasp executed without pretouch scanning.

- Rotation stage: After the gripper reaches the initial pose, the gripper rotates until the beams on both sides (left and right) of the sensor are broken. Then the line between the fingertips is recorded.
- Translation stage: The gripper begins to move along a new path that is perpendicular to the line found in the rotation stage. The gripper does this translation movement until the beams on both sides of the sensor are broken again. Again the line between the fingertips is recorded. The intersection of the two recorded lines is the position of the object.

Using the same framework as tissue grasping, the gripper gets to the initial pose based on the incomplete point cloud and bounding box of the object. Fig.9 demonstrates the process of the rotation stage. First, the gripper rotates 180 degrees around the x-axis of the gripper frame (Fig.9(a-d)). The pretouch sensing information can be seen in the 3D visualization in rviz. A green line indicates that there was nothing between the two fingers, a blue line means that only the beams on one side of the finger were broken, and the red line signifies that the beams on both sides of the finger were broken. The enlarged view in Fig.9(e) shows the pretouch sensing information gathered from the rotation scan. The object is not or only partially in the green or blue area, so a grasp in these two areas would be very likely to fail. The red area indicates the potential position of the object. A translation scan is then applied along the red area to determine the precise position of the object.

The whole process of grasping with rotation-translation scanning is demonstrated in Fig.10. The rotation detection comes first (Fig.10(a)). When both sides of the finger detect the object, the rotation scan stops, and the gripper rotates 90 degrees before initiating a translation scan. The scanning stops when both sides of the finger detect the object again (Fig.10(b)). The result of the scans is shown in Fig.10(b). The center position of the object is the intersection of the two red lines. A grasp is finally executed at this intersection point. A comparative experiment shown in Fig.11 is an example of a poor grasp that occurs when not using the transmissive optical sensor. The grasp is based only on the visual information from the Kinect. It can be concluded that the collected pretouch information is useful for grasping small objects. The attached video demonstrates all of the experiments in this paper.

V. CONCLUSION

Robotic grasping in unstructured environments has always been a challenge. One of the problems is incomplete sensing information of the object. Although vision/depth and tactile sensors can provide a lot of valuable information, certain materials (shiny or compliant) are hard to detect and tactile sensors tend to displace the object. Additional and accurate information about the object is of great importance just before grasping.

Considering the fundamental drawbacks of traditional vision/depth and tactile sensors, this paper proposed a new transmissive optical pretouch sensor in order to improve robotic manipulation. The sensor is composed of an emitter-receiver pair. Four beams of IR light are transmitted from the emitter side to the receiver side. The sensor is fully integrated into the PR2 robot's fingertips. It provides a simple, fast, and reliable way to detect objects that other sensors cannot.

Several experiments and corresponding heuristic algorithms are conducted to illustrate the sensor's applicability to environment perception and robotic grasping. Informed by an incomplete point cloud from the Kinect, it can trace the edge and find the corner of delicate materials before grasping. The center position of small objects can also be obtained after a rotation-translation scan by the sensor. We believe the sensing information provided by the transmissive optical pretouch sensor could ultimately be used to improve the accuracy of object recognition and categorization.

Our future work will focus on further development of the pretouch modality. As mentioned previously, the performance of each type of pretouch sensor is seriously degraded when operating on certain objects. These failures are unique for each sensor. For example, our transmissive pretouch optical sensor fails to detect transparent objects, seashell pretouch sensors cannot detect thin fabrics, and electric field pretouch sensors fail to detect light plastics. In the future, we will aim to combine these separate pretouch sensing methods into a single sensor. By leveraging multiple sensing techniques, our robotic platform will be able to detect, measure, and interact with a much wider range of objects.

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