International Journal of Scientific Trends- (IJST)
ISSN: 2980-4299
Volume 4, Issue 6, June - 2025
Website: https://scientifictrends.org/index.php/ijst
Open Access, Peer Reviewed, Scientific Journal

Development of Pid Controller Formula for Object Manipulation Using Sensor Systems

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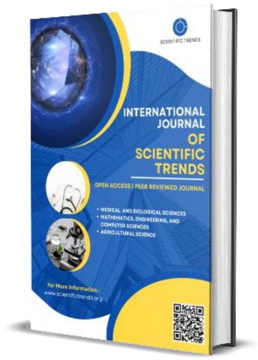

Abstract

This article reviews sensor-based vision and sensing technologies used in robotics and automated control systems for object detection and manipulation. Robotic manipulators operating in uncertain environments use a variety of sensors to ensure accuracy, reliability, and adaptability: visual sensors (cameras), force and torque sensors, rangefinders (LIDAR, ultrasound), and inertial sensors. This article analyzes inter-sensor integration, multi-sensor data processing, and algorithms for real-time object detection and manipulation. It also examines the possibilities of improving sensing systems with modern machine learning approaches.

Keywords: Sensor-based systems, Object manipulation, Visual sensing, Robotics, Multi-sensor integration, Uncertain environments, Force and torque sensors, Computer vision, Machine learning, Real-time algorithms.

Introduction

With the development of modern robotics and automated systems, the need for robots to operate autonomously in complex and uncertain environments is rapidly increasing. In particular, analyzing the environment in real time, detecting objects, and manipulating them accurately are among the critical tasks for robots. To accomplish these tasks, robots utilize various sensors, including visual sensors (cameras), force and torque sensors, LIDAR, ultrasonic sensors, and inertial measurement units (IMU).

Using sensor-based vision and perception systems, robots can not only detect objects but also assess their state, shape, position, and motion trajectories. Through such systems, a robot manipulator can precisely plan its movements relative to the object and adjust its actions in real time. These systems provide robust sensory feedback and adaptability, especially in uncertain, dynamic, or variable lighting environments.

Therefore, this research focuses on the technical and algorithmic foundations of object manipulation based on sensor-driven vision and perception technologies. Specifically, it examines sensor data fusion, object localization, motion planning, and the effectiveness of manipulation strategies. The results of this work aim to enhance the performance of industrial robots, service robots, and human-robot collaboration systems.

MAIN PART

These systems utilize various types of sensors, including visual sensors (cameras), distance-measuring sensors (LIDAR, ultrasonic), force and torque sensors, as well as inertial measurement units (IMUs).

Visual perception systems enable robots to detect, recognize, and determine the shape and position of objects. This process involves capturing images of the environment using 2D and 3D cameras, which are then analyzed by computer vision algorithms. In recent years, convolutional neural networks (CNNs), particularly models such as YOLO and Mask R-CNN, have allowed robots to identify objects in real time based on visual data. Using this visual information, robot manipulators determine how to approach an object, how to grasp it, and where to place it.

Alongside vision systems, force and torque sensors play a crucial role. These sensors detect physical interactions between the robot and the object, ensuring that manipulation tasks are performed safely and accurately. For instance, force sensors help prevent excessive squeezing of delicate objects or enable a robot to securely hold objects that may slip. Moreover, in human-robot collaboration scenarios, force sensing enhances sensitivity and safety.

To enhance the effectiveness of multi-sensor systems, sensor fusion—the technology of integrating data from multiple sensors—is widely employed. Each sensor provides distinct types of information; however, analyzing them collectively enables more reliable and accurate decision-making. For example, a camera supplies the object's visual representation, LIDAR measures the distance, and force sensors monitor the quality of contact. These data are integrated within a central control unit, which automatically adjusts the robot's movement trajectory and gripping force in real time.

The manipulation process operates in real time, with continuous monitoring based on sensor inputs. Techniques such as PID control, adaptive algorithms, and trajectory planning methods are applied. If the object's position changes or obstacles appear in the environment, the system adapts swiftly. Through feedback mechanisms, the manipulator's position, velocity, and force are constantly optimized.

Such sensor-based systems are extensively utilized today in industrial robots, medical robots, service robots, and even rescue robots operating in hazardous environments. For instance, in automated assembly lines, robots detect, grasp, and accurately place various components. In medicine, robots performing delicate operations rely on sensitive force sensors and vision systems to guide their movements. Similarly, rescue robots working in uncertain and obstacle-laden environments depend heavily on sensor-based vision and perception systems to locate and carefully manipulate objects.

Multiple fundamental physical and mathematical models underpin the detection and manipulation of objects by robot manipulators. Below are the core formulas and corresponding analyses for manipulation.

Visual detection of object position. If the camera captures the object coordinates in pixel format (u, v) and the depth sensor provides the Z coordinate, then the 3D coordinates in space are calculated as follows:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = Z * K^{-1} * \begin{bmatrix} u \\ v \\ 1 \end{bmatrix}$$

Here:
K – the camera matrix (intrinsic matrix), representing the optical properties of the camera;
(u, v) – the coordinates of the object in the image (in pixels);
Z – the depth to the object (in meters).

Force and torque sensing model. The force and torque measured by the sensor at the point of contact with the object are given by:

$$\vec{F}_{sensor} = \begin{bmatrix} F_x \\ F_y \\ F_z \\ M_x \\ M_y \\ M_z \end{bmatrix}$$

If excessive force is applied to the object (for example, $F_z > F_{max}$), the robot will stop its movement or automatically reduce the force:

$$F_{cmd} = \begin{cases} F_z, & F_z \leq F_{max} \\ F_{max}, & F_z > F_{max} \end{cases}$$

Motion Control and Feedback. The PID control algorithm is used to manage the position of the manipulator:

$$u(t) = K_p e(t) + K_i \int_0^t e(t)dt + K_d \frac{de(t)}{dt}$$

Here:
u(t) – output signal,
e(t) – error (the difference between the desired and actual position),
K_p, K_i, K_d – PID coefficients.
These formulas are crucial for ensuring the accuracy and stability of the robot manipulator.

Conclusion

Today, there is an increasing demand in the field of robotics for systems capable of interacting with the environment, making autonomous decisions, and rapidly adapting to various conditions. Vision and perception systems have become particularly critical for robots operating in real-world environments that are uncertain, dynamic, or previously unknown.

In this work, the role, operating principles, main components, and governing mathematical models of sensor-based systems in object manipulation were thoroughly studied. The aforementioned formulas form the mathematical foundation of sensor-based manipulation systems. They enable accurate determination of object position, control of manipulator movements, and ensure safety through perception systems. These models and calculations provide a basis for reliable robot operation in complex and uncertain environments.

For instance, in robotics, such systems help robots understand their surroundings and optimize their movements. In autonomous vehicles, vision-perception manipulators detect objects around the vehicle to maintain safety. In medicine, vision-perception manipulators assist in monitoring and analyzing patient conditions, facilitating diagnostics.

However, these systems are not capable of covering every possible variation or meeting every need. There are certain challenges and limitations related to the effectiveness of the technologies and their implementation.

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