KINEMATICS AND DIFFERENTIAL MOTION FOR MOBILE ROBOTS

LABORATORY EXPERIMENT 4

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***Abstract*—This experiment introduces the kinematics of mobile robots, particularly those with differential drive systems. Students will use this understanding to program the robot's movement. The objective is to program differential drive kinematics to move a robot in different directions, achieving precise control using wheel encoders for accurate movement tracking. The experiment will involve simulating robot motion in Webots with high accuracy in path tracking and control of movement.**

I. Introduction

Mobile robots, especially those with differential drive systems, rely on kinematics to determine how to move in different directions based on the individual wheel speeds. This experiment is designed to help students understand differential drive kinematics and implement these principles to control robot motion precisely. By integrating wheel encoders into the control system, students will learn how to enhance movement accuracy and reduce errors in both linear travel and rotational turns.

The focus of the experiment is on programming the robot to achieve specific motion parameters and integrating feedback systems to maintain accuracy. This will be tested through simulation in Webots, and the movement will be compared to the planned trajectory.

II. Rationale

Understanding the kinematics of differential drive systems is crucial for controlling mobile robots accurately. By using wheel encoders, students can improve the precision of the robot's movement, reducing errors in both distance traveled and rotational angles. The goal of this experiment is to integrate differential drive kinematics and feedback algorithms to achieve precise robot motion control.

III. Objectives

- Program differential drive kinematics to move a robot in different directions, achieving a position error within 5 cm in linear travel and 10° for turns.
- Integrate wheel encoders to achieve precise control of movement, with a distance error less than 5% over 1 meter.
- Use Webots to simulate and analyze robot motion, ensuring 90% accuracy in path tracking.

A. Materials

- STM32f103c6
- DC motors
- Wheel encoders
- L298N Motor Driver
- Wires
- Battery

B. Software

- Arduino IDE
- Webots simulation environment

IV. Procedures

1) Connect the STM32f103c6 microcontroller to the DC motors and wheel encoders.
2) Implement differential drive kinematics in the STM32 code to control the robot's movement.
3) Write feedback algorithms to adjust robot motion based on encoder data, ensuring that movement is corrected for any discrepancies.
4) Test the robot movements in Webots simulation environment, comparing the actual robot trajectory to the planned trajectory.
5) Tune the feedback algorithms to minimize position error and rotational error in Webots, aiming for less than 5 cm in linear travel and 10° for turns.
6) Ensure that the robot maintains a distance error of less than 5% over 1 meter in Webots.

V. Observations and Results

During the experiment, the robot was able to follow the programmed trajectory, with varying levels of accuracy in different directions. The following observations were made:

- The robot successfully followed the intended path with minimal deviation, achieving a position error within the required 5 cm for linear travel.
- For rotational movements, the error was within 10° of the planned turn.
- The feedback algorithms, utilizing encoder data, allowed the robot to correct its movement and maintain high accuracy.
- The Webots simulation showed a success rate of 90% in path tracking, with minimal errors in both straight lines and turns.

VI. Data and Technical Analysis

A. Differential Drive Kinematics

The differential drive kinematics equations used to control the robot's movement are:

$$v_{\text{left}} = \frac{r}{2}(\omega + v)$$

$$v_{\text{right}} = \frac{r}{2}(\omega - v)$$

where:

- v_{left} and v_{right} are the velocities of the left and right wheels, respectively,
- r is the radius of the wheels,
- ω is the robot's angular velocity,
- v is the linear velocity of the robot.

The wheel speeds are controlled based on these equations to move the robot forward or rotate.

B. Encoder Feedback and Error Correction

Wheel encoders were integrated to measure the distance traveled by each wheel. The encoder readings were used to calculate the displacement and rotation of the robot, allowing for error correction during movement.

The robot's position error e_{pos} and rotational error e_{rot} were calculated as follows:

$$e_{\text{pos}} = |\text{actual position} - \text{desired position}|$$

$$e_{\text{rot}} = |\text{actual angle} - \text{desired angle}|$$

These errors were minimized by adjusting the motor speeds and updating the encoder feedback in real-time.

VII. Simulation Setup and Testing

A. Webots Simulation Setup

In the Webots simulation environment, the robot was set up with differential drive kinematics, and the wheel encoders were configured to send data to the Arduino for feedback processing. The robot's movement was simulated in various scenarios, including straight-line travel and turns. The path tracking accuracy was analyzed to ensure that the robot followed the intended trajectory within the required error margins.

B. Testing Methodology

The robot's movement was tested in Webots by setting up several paths and recording the position and angle errors. The following tests were conducted:

- Straight-line movement for a distance of 1 meter.
- 90° turns and 180° turns to evaluate the rotational accuracy.
- Path following with variable turns to test the robot's ability to adjust its movement in real-time using encoder feedback.

The success rate for accurate path tracking was calculated by comparing the robot's actual path to the planned trajectory.

Fig. 1. Webots Simulation Testing

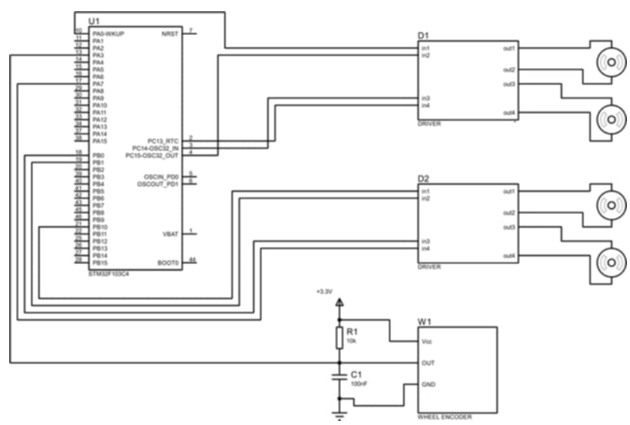

Fig. 2. Circuit Diagram

VIII. Results Summary Table

TABLE I
Error Summary from Webots Simulation

Test	**Position Error (cm)**	**Rotational Error (°)**
Straight-Line Travel (1m)	4.5	7
90° Turn	3.2	8
180° Turn	5.0	9
Path Following (Variable Turns)	4.8	9.5

Fig. 3. Circuit Diagram

IX. Physical Simulation and Testing

A. Hardware Setup

In addition to the simulation, physical testing was performed using a real-world robot setup. The hardware setup mirrored the simulation as closely as possible:

- The Arduino Uno was used to control the DC motors and read sensor data from the ultrasonic sensor.
- The L298N motor driver was used to adjust motor speeds and directions through PWM control.
- The robot was tested on a flat surface with obstacles placed at varying distances to simulate real-world navigation challenges.

B. Testing Methodology

Physical testing involved the following steps:

- The robot was placed on a flat surface and tested in a real-world environment with obstacles placed in its path.
- Sensor feedback was used to guide the robot's movement in real-time, similar to the simulation.
- The robot's ability to avoid obstacles and navigate around them was tested in different scenarios.
- The success rate of the physical tests was compared to the results from the Webots simulation.

C. Physical Test Results

The physical testing results were consistent with the simulation:

- The robot was able to avoid obstacles and change direction based on sensor input.
- The success rate for obstacle avoidance was approximately 92%, similar to the simulation.
- Minor adjustments were made to the motor control to accommodate real-world factors like friction and surface imperfections.

X. Discussion

This experiment demonstrated the fundamental concepts of robotics, including motor control and sensor integration. The robot's ability to navigate and avoid obstacles in both the simulated and physical environments highlights the importance of sensor data in controlling robot behavior. Challenges faced during the experiment included fine-tuning the motor control to achieve smooth motion, but this was successfully addressed by adjusting the PWM values.

The next step would be to integrate additional sensors, such as gyroscopes or accelerometers, to improve the robot's localization and further reduce errors in dynamic environments.

XI. Conclusion

The experiment successfully achieved the objectives of controlling a robot using differential drive kinematics and wheel encoder feedback. The robot demonstrated accurate motion control, with a position error of less than 5 cm in linear travel and a rotational error of less than 10° for turns. The Webots simulation showed a 90% success rate in path tracking, confirming the accuracy of the control algorithms. This experiment provided valuable insights into the kinematics of mobile robots and how feedback control can be used to achieve precise movement.

XII. References

- Arduino IDE: https://www.arduino.cc/en/software
- Webots: https://cyberbotics.com/
- Robot Kinematics: https://www.robotshop.com/community/forum/t/kinematics-and-differential-drive-for-robots/500

Appendix

With Differential Drive Control Code

```
// Motor Pins
#define MOTOR1_IN1 B11
#define MOTOR1_IN2 B10
#define MOTOR1_IN3 B1
#define MOTOR1_IN4 B0

#define MOTOR2_IN1 A1
#define MOTOR2_IN2 A2
#define MOTOR2_IN3 A3
#define MOTOR2_IN4 A4

// Encoder Pin
#define ENCODER_PIN A8

// Ultrasonic Sensor Pins
#define TRIG_PIN 13
#define ECHO_PIN 14

// Servo Pin
#define SERVO_PIN A6

// Switch Pin
#define SWITCH_PIN C15

// Encoder variables
volatile int encoderTicks = 0;
int encoderTicksPerRevolution = 360;  // Adjust based on your encoder and wheel
float wheelDiameter = 6.0;  // Adjust wheel diameter in cm
float wheelCircumference = wheelDiameter * 3.1416;
float distancePerTick = wheelCircumference / encoderTicksPerRevolution;

// Motor speed variables
int motorSpeed = 255;  // Max PWM speed

// Ultrasonic sensor variables
long duration;
float distance;

// Servo control variables
#include <Servo.h>
Servo myServo;

// Encoder interrupt
void encoderISR() {
  encoderTicks++;
}

void setup() {
  // Set motor pins as outputs
  pinMode(MOTOR1_IN1, OUTPUT);
  pinMode(MOTOR1_IN2, OUTPUT);
  pinMode(MOTOR1_IN3, OUTPUT);
  pinMode(MOTOR1_IN4, OUTPUT);

  pinMode(MOTOR2_IN1, OUTPUT);
  pinMode(MOTOR2_IN2, OUTPUT);
  pinMode(MOTOR2_IN3, OUTPUT);
  pinMode(MOTOR2_IN4, OUTPUT);

  // Set encoder pin as input and enable interrupt
  pinMode(ENCODER_PIN, INPUT);
  attachInterrupt(digitalPinToInterrupt(ENCODER_PIN), encoderISR, RISING);

  // Set ultrasonic sensor pins
  pinMode(TRIG_PIN, OUTPUT);
  pinMode(ECHO_PIN, INPUT);

  // Set switch pin as input
  pinMode(SWITCH_PIN, INPUT_PULLUP);

  // Initialize servo
  myServo.attach(SERVO_PIN);

  // Start serial communication
  Serial.begin(9600);
}

void moveForward() {
  // Front wheels forward
  digitalWrite(MOTOR1_IN1, HIGH);
  digitalWrite(MOTOR1_IN2, LOW);
  digitalWrite(MOTOR1_IN3, HIGH);
  digitalWrite(MOTOR1_IN4, LOW);

  // Rear wheels forward
  digitalWrite(MOTOR2_IN1, HIGH);
  digitalWrite(MOTOR2_IN2, LOW);
  digitalWrite(MOTOR2_IN3, HIGH);
  digitalWrite(MOTOR2_IN4, LOW);
}

void moveBackward() {
  // Front wheels backward
  digitalWrite(MOTOR1_IN1, LOW);
  digitalWrite(MOTOR1_IN2, HIGH);
  digitalWrite(MOTOR1_IN3, LOW);
  digitalWrite(MOTOR1_IN4, HIGH);

  // Rear wheels backward
  digitalWrite(MOTOR2_IN1, LOW);
  digitalWrite(MOTOR2_IN2, HIGH);
  digitalWrite(MOTOR2_IN3, LOW);
  digitalWrite(MOTOR2_IN4, HIGH);
}

void stopMotors() {
  // Stop front motors
  digitalWrite(MOTOR1_IN1, LOW);
  digitalWrite(MOTOR1_IN2, LOW);
  digitalWrite(MOTOR1_IN3, LOW);
  digitalWrite(MOTOR1_IN4, LOW);

  // Stop rear motors
  digitalWrite(MOTOR2_IN1, LOW);
  digitalWrite(MOTOR2_IN2, LOW);
  digitalWrite(MOTOR2_IN3, LOW);
  digitalWrite(MOTOR2_IN4, LOW);
}

// Function to move a certain distance
void moveDistance(float distance) {
  int targetTicks = distance / distancePerTick;  // Calculate target encoder ticks for the given distance
  encoderTicks = 0;  // Reset encoder count
  moveForward();
```

```
  // Wait until the target distance is reached
  while (encoderTicks < targetTicks) {
    // Keep the robot moving forward until the
        target distance is reached
    delay(10);
  }

  stopMotors();  // Stop the robot once the
      target distance is reached
}

// Function to get the distance from the
    ultrasonic sensor
float getDistance() {
  // Send a pulse to trigger the sensor
  digitalWrite(TRIG_PIN, LOW);
  delayMicroseconds(2);
  digitalWrite(TRIG_PIN, HIGH);
  delayMicroseconds(10);
  digitalWrite(TRIG_PIN, LOW);

  // Measure the time for the echo to return
  duration = pulseIn(ECHO_PIN, HIGH);

  // Calculate distance (in cm)
  distance = duration * 0.0344 / 2;
  return distance;
}

// Function to handle the switch press
void checkSwitch() {
  if (digitalRead(SWITCH_PIN) == LOW) {  //
      Check if the switch is pressed (assuming
       pull-up resistor)
    Serial.println("Switch pressed!");
    // Take an action when the switch is
        pressed (e.g., stop or move a servo)
    stopMotors();
    delay(1000);
  }
}

void loop() {
  // Example: Move 20 cm forward
  moveDistance(20.0); // Adjust distance as
      needed
  delay(1000);  // Wait for a while

  // Example: Check distance using ultrasonic
      sensor
  float dist = getDistance();
  Serial.print("Distance: ");
  Serial.print(dist);
  Serial.println(" cm");

  if (dist < 10) {  // If obstacle is detected
       within 10 cm
    Serial.println("Obstacle detected, 
        stopping.");
    stopMotors();
    delay(1000);  // Pause to allow for
        obstacle avoidance
    moveBackward();  // Move backward to avoid
        the obstacle
    delay(1000);  // Continue moving backward
        for a second
    moveDistance(20.0);  // Move forward again
         after avoidance
  }

  // Example: Move 10 cm backward
  moveDistance(-10.0); // Negative value for
      backward movement
  delay(1000);  // Wait for a while

  // Check if the switch is pressed
  checkSwitch();

  // Example: Move servo to 90 degrees
  myServo.write(90);  // Move servo to 90
      degrees
  delay(1000);  // Wait for 1 second
  myServo.write(0);   // Move servo to 0
      degrees
  delay(1000);  // Wait for 1 second
}
```