T.C.

AYDIN ADNAN MENDERES UNIVERSITY

GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

MASTER’S PROGRAMME IN DEPARTMENT OF MECHANICAL ENGINEERING

DYNAMIC MODELING OF TWO IDENTICAL COUPLED SPHERICAL ROBOTS

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TWO IDENTICAL COUPLED SPHERICAL ROBOTS

İsmail Hakkı SAĞSÖZ

MASTER’S THESIS

SUPERVISOR

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APPROVAL AND ACCEPTANCE

The thesis titled "DYNAMIC MODELING OF TWO IDENTICAL COUPLED SPHERICAL ROBOTS", prepared by İsmail Hakkı SAĞSÖZ, a student of Department of Mechanical Engineering at T.C. Aydın Adnan Menderes University, Graduate School of Natural And Applied Science, was accepted as a Master's Thesis by the jury below.

Date of Thesis Defence: 23/08/2021

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APPROVAL:

This thesis was approved by the jury above in accordance with relevant articles of the Aydın Adnan Menderes University Graduate Education and Examination Regulations and was approved on the.......................by from the Board of Directors of the Graduate School of Science in the .... numbered decision.

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Institute Director

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İsmail Hakkı SAĞSÖZ

(Mechanical Engineer)

CONTENTS

LIST OF SYMBOLS AND ABBREVAITIONS

mA: Milliamper

v: Volt

R: Radius

t: Time

sec: Second

rad: Radian

N: Newton

g: Gram

m: Meter

mm: Millimeter

v: Lineer Velocity

kb: Kilobyte

MHz: Megahertz

ω**:** Angular Velocity

3D: Three-Dimensional

DC: Direct Current

S: Single Robot

T: Two Robots

S1: Spherical Robot 1 (Right)

S2: Spherical Robot 2 (Left)

rpm: Revolutions Per Minute

k_T**:** Coefficient of Torsional Spring

nr_{max}**:** Maximum Speed of DC Gear Motors

DAEDALUS: Descent And Exploration in Deep Autonomy of Lava Underground Structures

KisBot: Kyungpook national university Intelligent Spherical robot

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ÖZET

BİRBİRİNE BAĞLI İKİ ÖZDEŞ KÜRESEL ROBOTUN DİNAMİK MODELLENMESİ

İsmail Hakkı S. Aydın Adnan Menderes Üniversitesi, Fen Bilimleri Enstitüsü, Makine Mühendisliği Bölümü Yüksek Lisans Programı, Yüksek Lisans Tezi, Aydın, 2021.

Amaç: Bu araştırma, küresel robotların denge, yalpalama ve kayma gibi problemleri ve çok yönlü mobil robotların viraj alma problemlerini çözmek için tasarlanmış birbirine bağlı iki özdeş küresel robotun dinamik modellemesini incelemek amacıyla yapılmıştır. Birbirine bağlı iki özdeş küresel robotun dinamik modellemesindeki temel amacımız, çok yönlü mobil robotlarda mecanum tekerlekler yerine birbirine bağlı iki özdeş küresel robot tasarımı kullanarak çok yönlü bir mobil robot tasarlamaktır.

Materyal ve Yöntem: Bu tezde, MSC Adams programı kullanılarak tek bir küresel robot ve birbirine bağlı iki özdeş küresel robot tasarımının dinamik analizleri yapılmıştır. Bu dinamik analizler sonucunda tasarımımızın uygulanabilirliği kontrol edilmiştir. Sonuç olarak, dinamik analiz sonuçlarını da kontrol etmek için farklı yol profilleri üzerinde deneysel çalışmalar yapılmıştır.

Bulgular: Analiz ve deneylerden elde edilen sonuçlara göre, birbirine bağlı iki özdeş küresel robot tasarımının dinamik modellemesinin uygulanabilir olduğu görülmüştür.

Sonuç: Bu çalışmada birbirine bağlı iki özdeş küresel robot tasarımının dinamik modellemesinin uygulanabilir olduğu anlaşılmıştır.

Anahtar kelimeler: Küresel Robotlar, Dinamik Analiz, MSC Adams, Birbirine Bağlı İki Özdeş Küresel Robot

ABSTRACT

DYNAMIC MODELING OF TWO IDENTICAL COUPLED SPHERICAL ROBOTS

İsmail Hakkı S. Aydın Adnan Menderes University, Graduate School of Natural and Applied Sciences, Master's Programme in Department of Mechanical Engineering, Master Thesis, Aydın, 2021.

Objective: This research was carried out in order to examine the dynamic modeling of two identical coupled spherical robots that are designed to solve problems such as balance, wobble, and skiddingof spherical robots and cornering problems of omnidirectional mobile robots. Our main goal in the dynamic modeling of two identical coupled spherical robots is to design an omnidirectional mobile robot by using two identical coupled spherical robot designs instead of mecanum wheels in omnidirectional mobile robots.

Material and Methods: In this thesis, dynamic analyses of a single spherical robot and two identical coupled spherical robots design were made by using the MSC Adams program. As a result of these dynamic analyses, the applicability of our design has been checked. As a consequence, experimental studies were made on different road profiles in order to check the result of dynamic analyses, too.

Results: According to results that made of analyses and experiments, the dynamic modeling of two identical coupled spherical robots design has been seen to be applicable.

Conclusion: It was understood in this study that the dynamic modeling of two identical coupled spherical robots design is applicable.

Keywords: Spherical Robots, Dynamic Analysis, MSC Adams, Two Identical Coupled Spherical Robots

1. INTRODUCTION

Spherical robots are mobile robots, in which all components are placed in a sphere that also acts as an outer shell, and the surface of this sphere is rolled on the ground and the movement is performed (Kayacan, 2010).

When we examine the usage areas of the spherical robots, we see that they are quite wide. Especially, Jones (Jones, 2001), Ylikorpi (Ylikorpi et al., 2005), which are designed for use in space studies, and Mine Kafon (Hassani, 2008), which can be used to clear mined areas, are spherical robot designs that run with wind energy. Other striking designs are the underwater spherical robot designed (MIT, 2011) to detect leaks in nuclear reactor cooling systems, the spherical robot that used in agriculture (Hernández et al., 2013), the Rotundus Groundbot (Rotundus, 2010) security robot designed for surveillance, and the Surveillance Robot that can easily navigate on snowy and muddy surfaces (Knight, 2005), are such these designs.

In addition, the first studies on the kinematics and dynamics of spherical bodies date back to the studies of E. Routh and S.A. Chaplygin, and such studies are still being examined. (Borisov et al., 2019, Campos et al., 2006, Borisov et al., 2008) Since that time period, many studies havebeen carried out on the kinematics and dynamics of spherical robots with various components. (Chase and Pandya, 2012, Crossley, 2006) These studies were carried out by considering different road profiles from a flat horizontal plane to road profiles with different geometries (Roozegar andMahjoob, 2016, Tafrishi et al., 2016, Ylikorpi et al., 2017, Roozegar et al., 2017).

Especially, when we examine the Kinematics of Spherical Robots Rolling on a 3D Terrain by Saeed Moazami et al. in 2019, there are some points to be aware of. Different rolling and steering spherical robots can have different maximum tilt angles to be considered according to their mechanical design. Gravity can make it impossible to roll in some directions, and the robot cannot always roll at the angular speed recommended by the controller, and this keeps going. These are the issues that need to be addressed in the integration of kinematics and dynamics (Moazami et al., 2019b).

Spherical robots have some advantages over other mobile robots. First of all, we can say that they have only a single point of contact on the ground with minor friction for movement. Due to this motion, they will be able to save energy. Secondly, because of their spherical structure, they can move even in tightly constrained areas. Thirdly, the spherical shell of spherical robots protects the inner structure against external factors. By modifying their structures, they can even be made liquid and gas-proof. Finally, there is no possibility for a spherical robot to tip over, turn over, and then lose mobility (Nagai, 2008).

On the other hands, spherical robots have a few problems. These are balance problems, wobble, and skidding. Gyroscopic stabilizers can be used to solve spherical robot problems but this solution will be costly. Because of this costly solution, we designed two identical coupled spherical robots in order to solve problems of spherical robots. Besides, this design by modifyingand can be used for transport and viewing, too.

Furthermore, when we look at omnidirectional mecanum wheel mobile robots that can move in all directions, we will see that these robots have difficulty cornering. Because spherical robots can easily move in every direction, this problem will disappear, too when we use two identical coupled spherical robots instead of mecanum wheels. Due to the fact that cornering problemsof omnidirectional mobile robots and problems such as balance, wobble, and skidding of spherical robots, we designed two identical coupled spherical robots. Our ultimate goal in Dynamic Modeling of Two Identical Coupled Spherical Robots is to design an omnidirectional mobile robot using this design.

The issues that need to be considered while driving spherical robots in 3D terrains, which are mentioned in the Kinematics of Spherical Robots Rolling on a 3D Terrain Research Article by Saeed Moazami et al. in 2019 (Moazami et al., 2019b), are going to be minimized with this design.

In this thesis, dynamic analyses of a single spherical robot and two identical coupled spherical robots design were made by using the MSC Adams program. These analyses helped us to compare the dynamic behavior of single and double spherical robots under different road conditions and the same conditions. As a result of these analyses, the applicability of our design was checked. In this context, our experimental studies were begun after two identical coupled spherical robots dynamic models are produced.

2. LITERATURE REVIEW

Mobile robots vary widely. (Rubio F. et. all., 2019) has made a comprehensive classification of these. In this thesis, since the usage areas of spherical robots are very wide from water to space, it was preferred to show it by opening a separate sub-title, not in wheeled robots.

2.1. Mobile Robots

Currently, mobile robotics technology is one of the fastest expanding fields in the scientific world. Thanks to the wide availability of mobile robots, they can be used instead of humans in many fields (Rubio et al., 2019).

We can classify into 6 major categories to mobile robots:

2.1.1. Stationary Robots (Arm / Manipulator)

Industrial robots and manipulators can be examined in this section. The use of these robots, which can perform many physical operations, is quite common. Kuka, Fanuc Kawasaki, etc. examples of such robots can be given.

Other significant fixed robotic systems are gripping devices. Gripping is an essential part of carrying, and gripping devices from the start were designed primarily to assist people in carrying tasks and offer solutions that can be classified into two categories: these are prostheses and instruments (Ceccarelli, 2013).

As seen in the study of Carlos et al., gripping devices started to be used in many sectors. Especially the use in industry draws attention (Carlos et al., 2013).

Figure 1: Kr quantec nano (Kuka,)

2.1.2. Land-Based Robots

2.1.2.1. Wheeled Mobile Robots

Wheels are an indispensable part of the motion system in mobile robotics. Many mobile robots have been designed by changing the number of wheels or their geometry. They are also used in areas such as transportation and imaging.

Wheeled robots have one notable drawback. This is the unbalanced movement they encounter on rough terrain and low friction surfaces (Rubio et al., 2019).

There are four basic wheel types (Campion and Chung, 2008, Ferriere et al., 1996). These are, Fixed standard wheel, Castor wheel, Swedish wheel, and Ball or spherical wheel.

The most significant things in modeling mobile robot kinematics and dynamics are the type and number of wheels (Campion et al., 1996).

In general, wheeled robot studies focused on balance, maneuver, and control (Shiroma et al., 2006, Lee and Jung, 2016). The most important feature of wheeled robots is that they can remain balanced due to the movement of the wheels based on contact with the ground.

Often, designs with more than two wheels have been developed to provide stability (Stol, 2010, Beniak and Pyka, 2016, Cui et al., 2016), (Campion and Chung, 2008). If more than three wheels are preferred, it should not be forgotten that a suspension system is also needed (Bałchanowski, 2012).

For other types of wheels, see (Laney and Hong, 2006).

According to the drive system, WMRs can be classified:

- Differential drive WMRs
- Car-type WMRs
- Omnidirectional WMRs (Williams et al., 2002, Asama et al., 1996, Lafaye et al., 2014).
- Synchro drive WMRs7

• Single-Wheeled Robots

An unstable system, unicycles require lateral and vertical stability controls to maintain their equilibrium position. Han et al. His work is a good example of this (Han et al., 2013).

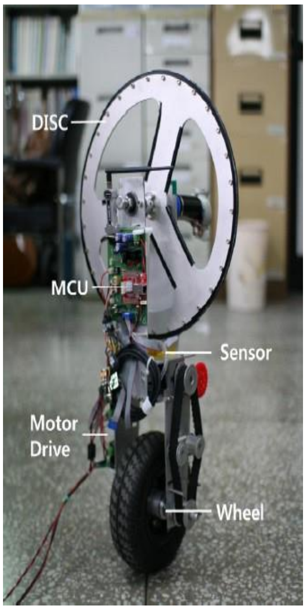


Figure 2: Single-wheeled robot (Han et al., 2013)

• **Two-Wheeled Robots**

These robots are controlled by two independent actuators. Its wheels are similar and parallel conventional wheels (Chan et al., 2013).

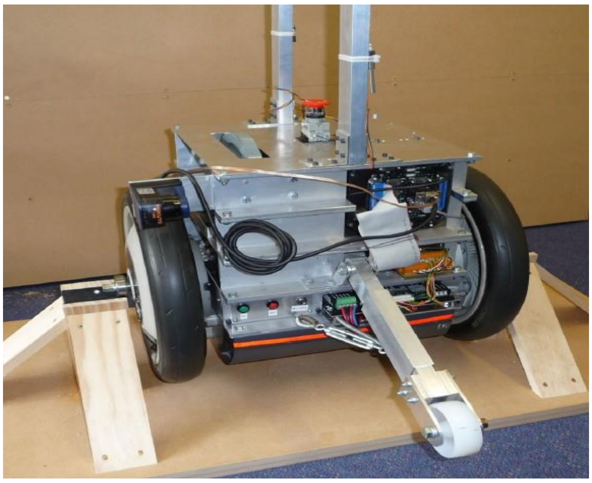


Figure 3: Two-wheeled robot (Stol, 2010)

• **Three-Wheeled Robots**

Three-wheeled robots have two main controls. The first of these is differentially steered, the second is two-wheel-driven steering and the third is driven by an actuator (Kim and Kim, 2013).

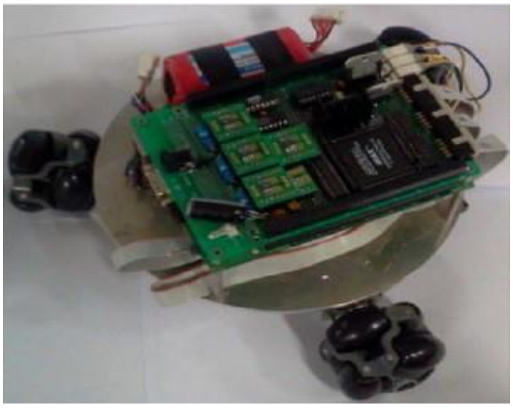


Figure 4: Three-wheeled omnidirectional mobile robot (Kim and Kim, 2013)

• **Four-Wheeled Robots**

It is known that these robots are more balanced than three-wheeled robots due to their center of gravity position. Different wheel controls are available. Car-like mobile robots are very important (Lerin et al., 2012, Cherif et al., 1999). Google's self-driving car, (Poczter and Jankovic, 2014) AIVs and Hybtor Robot belong to this type.

Figure 5: Four-wheeled robot (Wheeled(Four),)

• **Five-Wheeled Robots**

Since contact and balance increase in five-wheeled robots, these robots are more suitable for use on rough terrain (Xu et al., 2010). They designed the first five-wheeled robot. (Ani et al., 2011) is another example of a five-wheeled robot in his design.

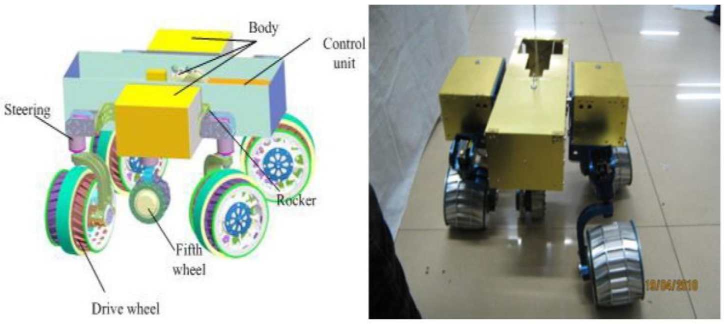


Figure 6: Five-wheeled robot (Xu et al., 2010)

• Six-Wheeled Robots

We can give examples of six-wheeled robots such as the Sojourner robot from the Mars Pathfinder mission in 1997, (Bajracharya et al., 2008) Spirit and Opportunity in 2004 (Carsten et al., 2007), and Curiosity in 2012 (Grotzinger et al., 2012).

In addition, Shrimp (Estier et al., 2000) and Marsokhod (Wettergreen et al., 1997) are other such robots.

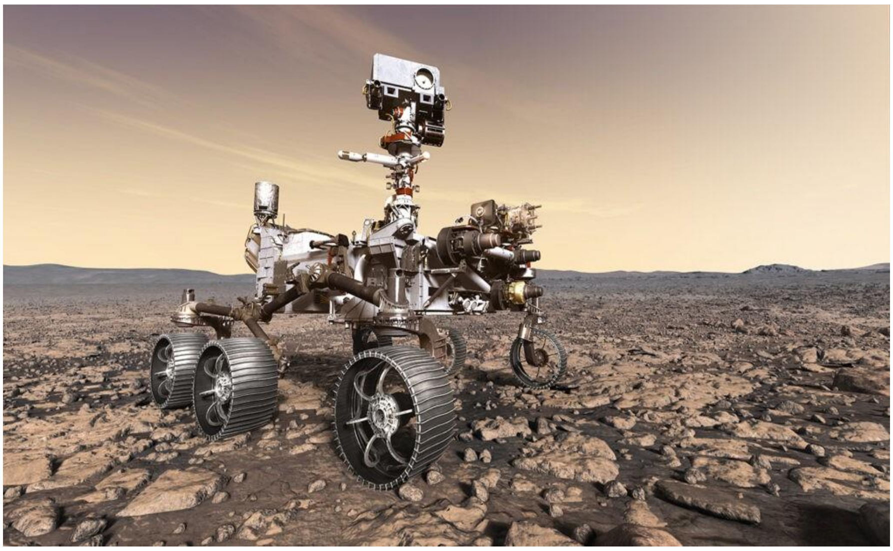


Figure 7: Six-wheeled robot (nasa's perseverance) (Wheeled(Six), 2021)

• More than Six Wheels Robots

The octopus robot is a WMR that can handle rough terrain autonomously without getting stuck with obstacles (Lauria et al., 2002).

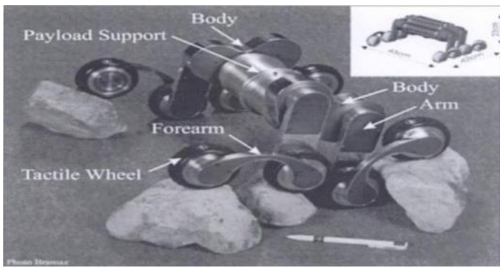


Figure 8: More than six wheeled robot (the octopus) (Lauria et al., 2002)

2.1.2.2. Walking or Legged Mobile Robots

Another type of movement used in mobile robots is movement using legs. Mobile robots with legs have several advantages over wheeled mobile robots. These are better mobility, better energy efficiency, better stability, and a smaller impact on the ground (Hirose et al., 1991).

• One-Legged Robots

The biggest disadvantage of single-legged robots is that they topple over when standing still. Uniroo is an example of a one-legged robot (Zeglin, 1991).

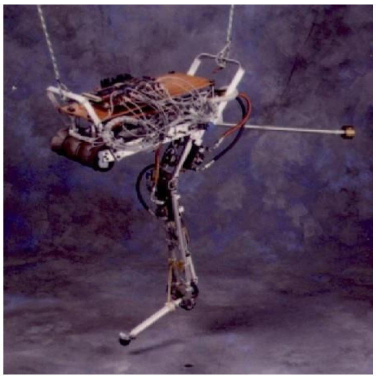
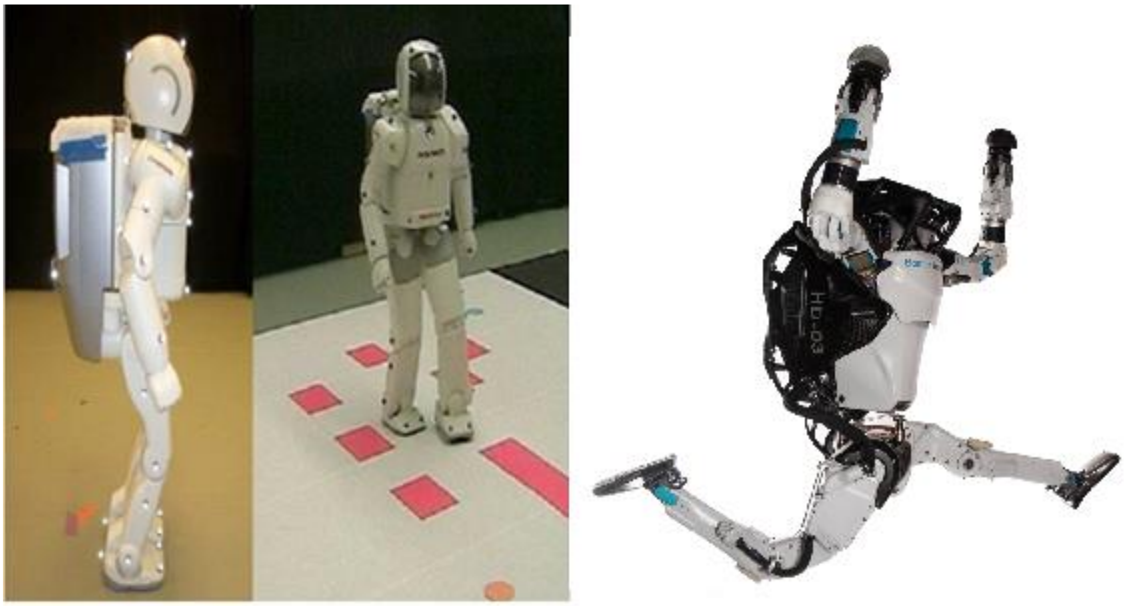


Figure 9: One legged robot (Legged(One), 1991)

• Two-Legged or Humanoid Robots

Humanoid robots are one of the most important types of walking robots. The movement of bipedal robots depends on dynamic stability. Today, studies on the construction of humanoid robots continue rapidly. ASIMO and ATLAS are the most famous humanoid robots known (Yanase and Iba, 2006, Chestnutt et al., 2005, BostonDynamics,).



(a) (b)

Figure 10: Two legged robot (a) honda asimo (chestnutt et al., 2005)
(b) bostondynamics atlas (BostonDynamics,)

• Three-Legged Robots

STriDER is a good example of this type of robot. Due to their tripod-like structure, they are stable and have simple kinematic (Heaston et al., 2007).

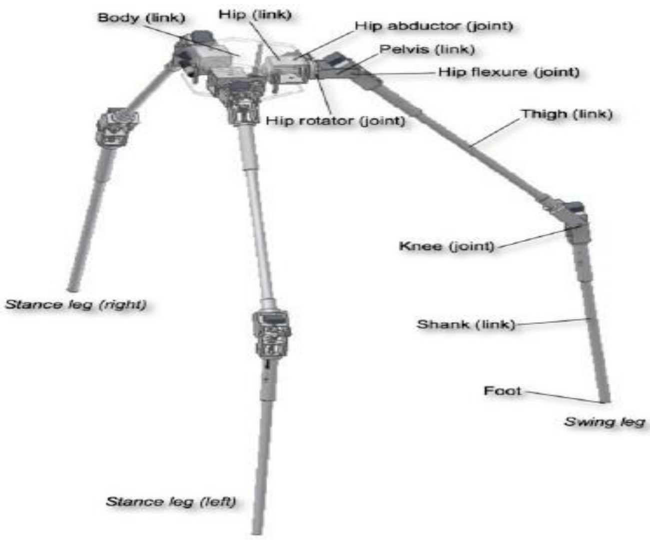
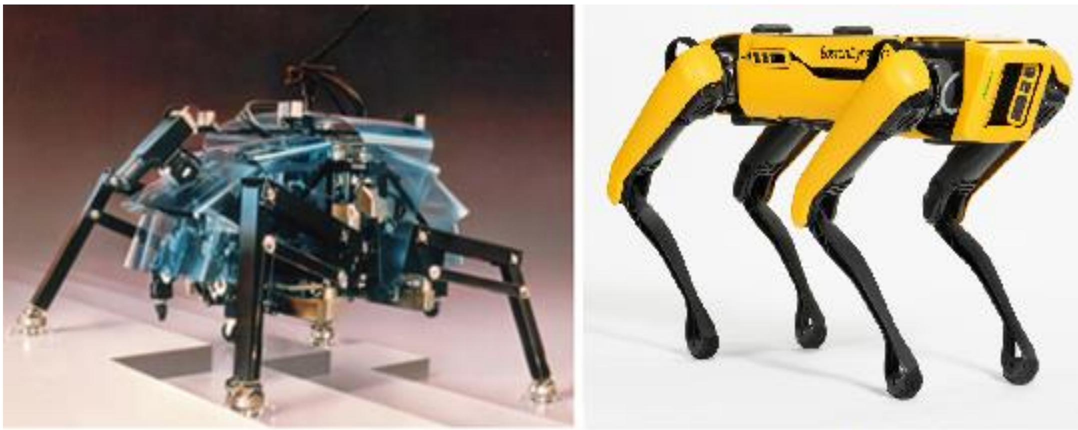


Figure 11: Three legged robot (Heaston et al., 2007)

• **Four-Legged Robots**

In this type of robot, attention should be paid to the step coordination that will provide balance during the movement (Hirose et al., 2009). At the moment, one of the most famous four-legged robots is BostonDynamics' Spot Robot.



(a) (b)

Figure 12: Four legged robot (a) titan iv (Hirose et al., 2009)
(b) bostondynamics' spot robot (BostonDynamics,)

• **Five-Legged Robots**

Besari et al. The robot he developed can be given as an example. Their use is not very common (Besari et al., 2009).

Figure 13: Five legged robot (Besari et al., 2009)

• **Six-Legged (Hexapod) Robots**

Hexapod can be given as an example of walking robots, a common architecture (Barreto et al., 1998, Esteban et al., 2016, Skaburskyte˙ et al., 2016).

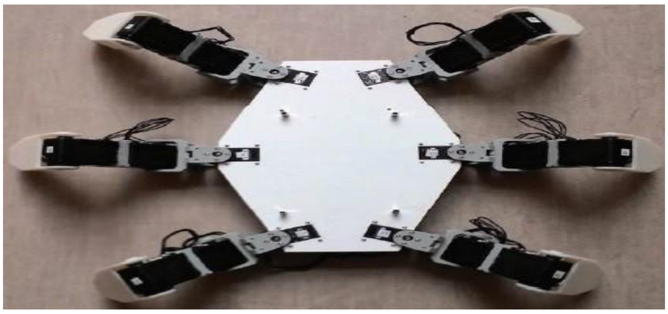


Figure 14: Six legged robot (Esteban et al., 2016)

• **More than Six-Legged Robots**

Dante robot is a good example of this kind of robot. They are generally designed with inspiration from spiders (Bares and Wettergreen, 1999).

Figure 15: More than six legged robot (Bares and Wettergreen, 1999)

2.1.2.3. Tracked Robots

The biggest advantage of crawler robots is that they move easily on soft and loose floors due to the high contact between the pallets and the ground (Schiele et al., 2008, Takayama, 2003).

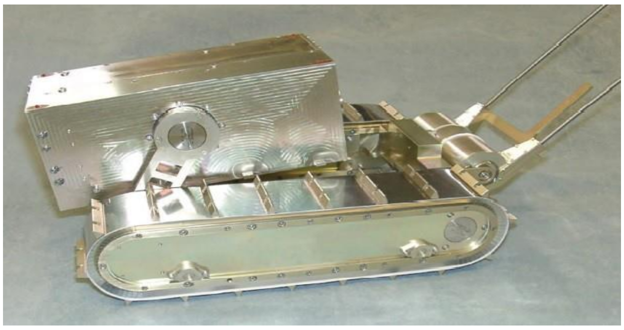


Figure 16: Tracked robot (Takayama, 2003)

2.1.2.4. Hybrid Robots

These robots are robots that are a combination of several of the above types of robots. Hybrid mobile robots can be classified into four categories, according to Bruzzone1 and Quaglia (Bruzzone and Quaglia, 2012).

- Leg-wheel hybrid locomotion systems (Tadakuma et al., 2010, Vargas et al., 2016).
- Leg-track hybrid locomotion systems (Yokota et al., 2006).
- Wheel-track hybrid locomotion systems (Kim et al., 2010a).
- Leg-wheel-track hybrid locomotion systems (Michaud et al., 2005).

2.1.3. Air-Based Robots

Unmanned aerial vehicles, called drones, are robots inspired by the working principles of helicopters.Today, the most advanced ones perform land and take on without operator control (Paul, 2013).

2.1.4. Water-Based Robots

Underwater robots, which are an important type of mobile robots, are used to explore the ocean and underwater areas (Wang et al., 2017).

2.1.5. Others

There are mobile robots that are difficult to classify in terms of movement parameters. For instance:

• Snake-Like Robots

These robots have several key advantages. These are because they are omnidirectional, acquiring behaviors that are not limited to climbing, crawling, and swimming (Kamamichi et al., 2006, Klaassen and Paap, 1999).

• Worm-Like Robots

These use peristalsis, the same method of locomotion used by worms. This movement method is especially effective in restricted areas (Boxerbaumet al., 2009), (Schulke et al., 2011).

• Nanorobots

They are robots whose components are on the nanometer scale.

• Cooperative Robotics

It is about coordinated control of robot teams.

• Cooperative Nanorobotics

It is about application to nanorobots with a difference in scale and capabilities.

2.1.6. Spherical Robots

Spherical robots are mobile robots, in which all components are placed in a sphere that also acts as an outer shell, and the surface of this sphere is rolled on the ground and the movement is performed (Kayacan, 2010).

2.1.6.1. History of Spherical Robots

The first spherical robot example is a spring toy patented in 1893 (U.S. Patent 508,558). The design was developed by B. Shorthouse in 1906. Since then, spherical robots have been used for various purposes.

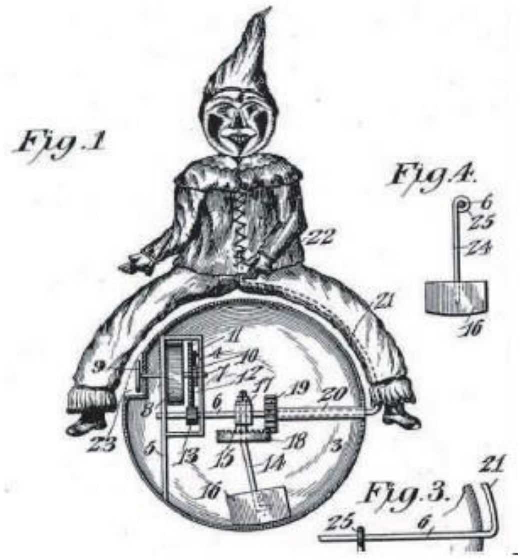


Figure 17: Mechanical toy by e.e. cecil (u.s. patent 933,623)

Another popular movement system was improved in 1918 by A.D. McFaul. Also called hamster ball. This design, which works with an internal drive unit, is still used in many designs today (Nagai, 2008).

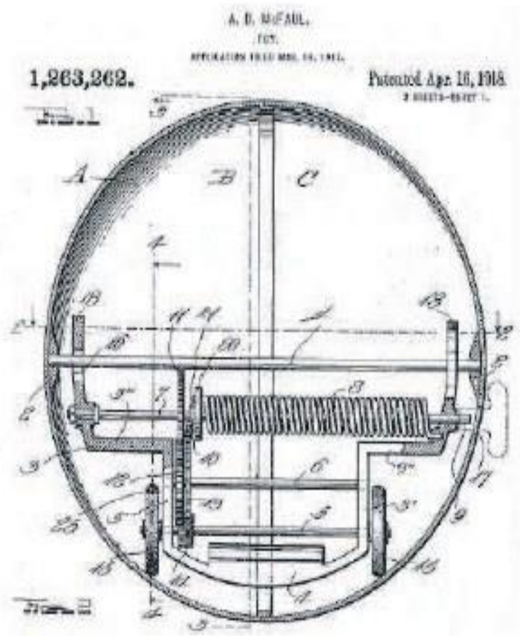


Figure 18: The hamster ball design by a.d. mcfaul (u.s. patent 1,263,262)

In 1957 J.M. With the design developed by Easterling, batteries and electric motors were used instead of springs as power sources. Along with the addition of the electrical system to the spherical robots, it brought many functions such as sensing and switching to the robot (Nagai, 2008).

2.1.6.2. Spherical Robot Design Configurations

When we examine spherical robots' design configurations, we will see that there are lots of design configurations.

In Figure 19, some spherical robot design configurations were shown.

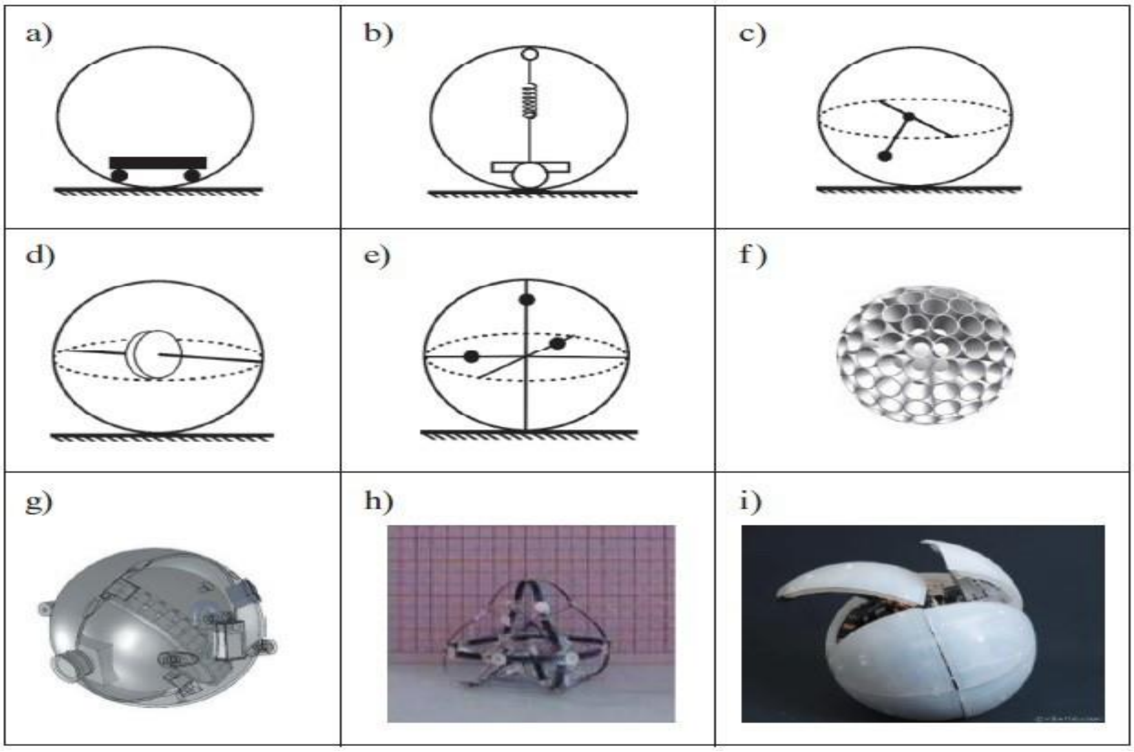


Figure 19: Spherical robot design configurations: a) internal cart configuration (Alves and Dias, 2003,Schroll, 2010) b) internal cart with shaft and roller (Jaimez et al., 2012) c) pendulumwith an axle (Schroll, 2010, Landa and Pilat, 2015, Moazami et al., 2019a) d) flywheel-based design (Chemel et al., 1999, Schroll, 2010) e) multiple mass-shifting design (Mukherjee, 2010, Schroll, 2010) f) wind-powered robot (Antol, 2003) g) underwater robot (MIT, 2011) h) deformable body design (Sugiyama et al., 2005) i) morphex (Halvorsen, 2014) (Firlej, 2015)

- **Universal Wheel**

A design that incorporates the principles of barycenter offset is BHQ-3 (Zhan et al., 2011). BHQ series robots are named after the Boltzmann-Hamel equation of their dynamic model. This design is a combination of hamster wheel and internal drive unit design (Zhan et al., 2011), (Chase and Pandya, 2012).

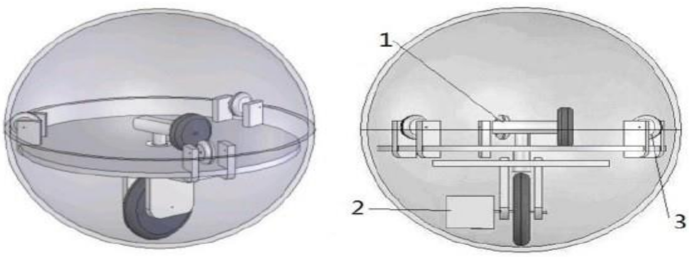


Figure 20: Structure of bhq-3: 1–motor, 2–motor, 3–sponge wheels (Zhan et al., 2011)

• **Hopping Spherical Robot**

In a spherical robot design designed by L. Bing, the robot driven by the pendulum was given the ability to jump (Li et al., 2009). Thanks to the mechanism shown in Figure 21, the spherical robot jumps in the desired angle and direction after the mechanism reconfigures itself (Chase and Pandya, 2012).

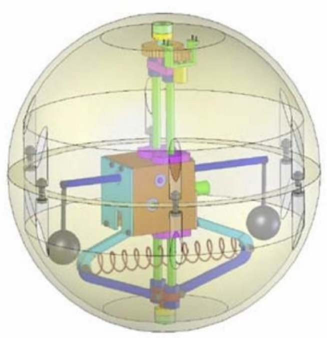


Figure 21: Image of hopping spherical robot and its jumping mechanism (Li et al., 2009)

• **KisBot**

This spherical robot, called KisBot, have that includes arms and two types of driving mode: rolling and wheeling (Kim et al., 2010b).

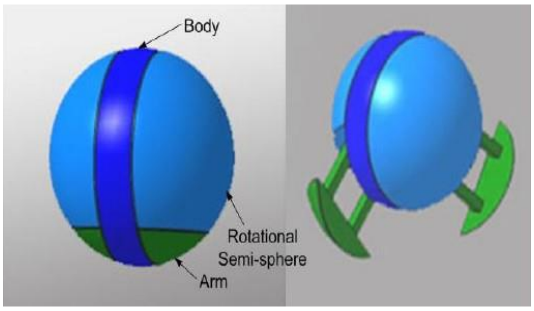


Figure 22: Design drawing of kisbot (Kim et al., 2010b)

• **A Deformable Spherical Planet Exploration Robot**

In this design, a deformable spherical planetary exploration robot is introduced to perform environmental sensing mission in space or in extreme conditions (Liang et al., 2013).

Figure 23: Image of the robot without airbags (Liang et al., 2013)

• **A Novel Amphibious Spherical Robot**

A new amphibious spherical robot called ASR-III, this robot is capable of hybrid locomotion (Xing et al., 2018).

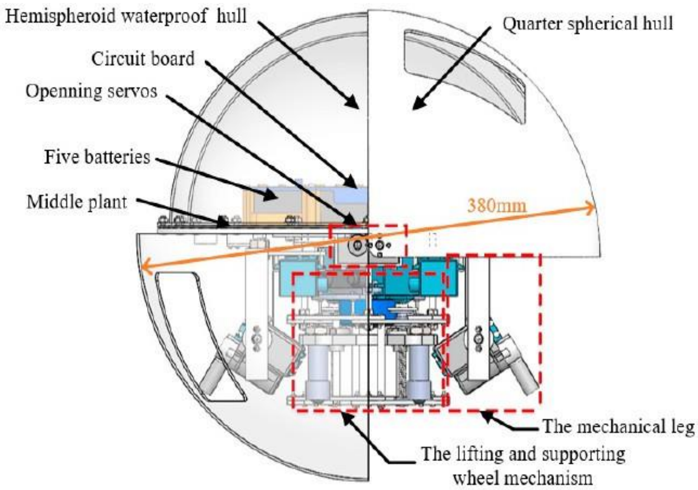


Figure 24: The novel amphibious spherical robot iii (asr-iii) (Xing et al., 2018)

• **Indoor Exploration**

Potapov et al. This design developed by is a good example of imaging application of spherical robots (Potapovet al., 2020).

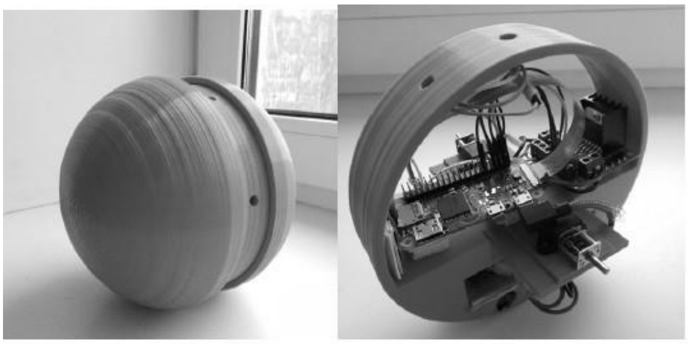


Figure 25: External and internal view of spherical robot v1 (Potapov et al., 2020)

• **Differential Drive System**

Such spherical robots working with differential drive are divided into three parts. These sections are two independently rotating hemispheres driven by an electric motor and an inner body that carries other equipment (Crossley, 2006).

Figure 26: Front view of ball robot (Raura, 2016)

• **DAEDALUS**

(''The DAEDALUS mission design concept aims at exploring and characterizing the entrance oflunar lava tubes within a compact, tightly integrated spherical robotic device, with a complementary payload set and autonomous capabilities.'') (Rossi et al., 2021).

Figure 27: The different modes of the sphere. top-left: mode 1, desending mode. top-right: mode 2, rolling mode. bottom-left mode 3, scanning mode. bottom-right: mode 4, obstacle mode (Rossi et al., 2021)

2.1.6.3. Advantages and Disadvantages of Spherical Robots

When we compare spherical robots with other mobile robots, we can say that spherical robots have some advantages over other mobile robots.

First of all, when we examine their movement, they have only a single point of contact on the ground with minor friction for movement. Due to this motion, they will be able to save energy. Secondly, because of their spherical structure, they can move even in tightly constrained areas. Thirdly, the spherical shell of spherical robots protects the inner structure against external factors. By modifying their structures, they can even be made liquid and gas-proof. Finally, there is no possibility for a spherical robot to tip over, turn over, and then lose mobility (Nagai, 2008).

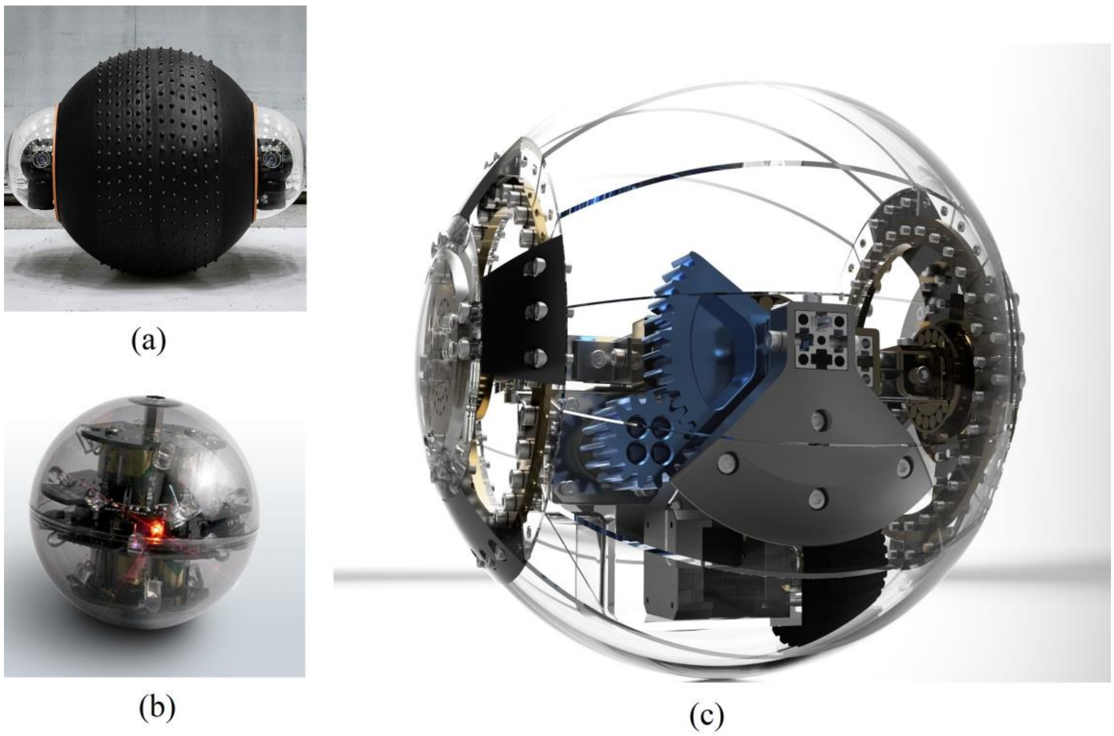


Figure 28: Images of some instance spherical robots (a) (Soulask, 2018) (b) (Elekit,) (c) (Autodesk,)

Spherical robots are due to the fact that their spherical structure, they have a few problems. These are balance problems, wobble, and skidding.

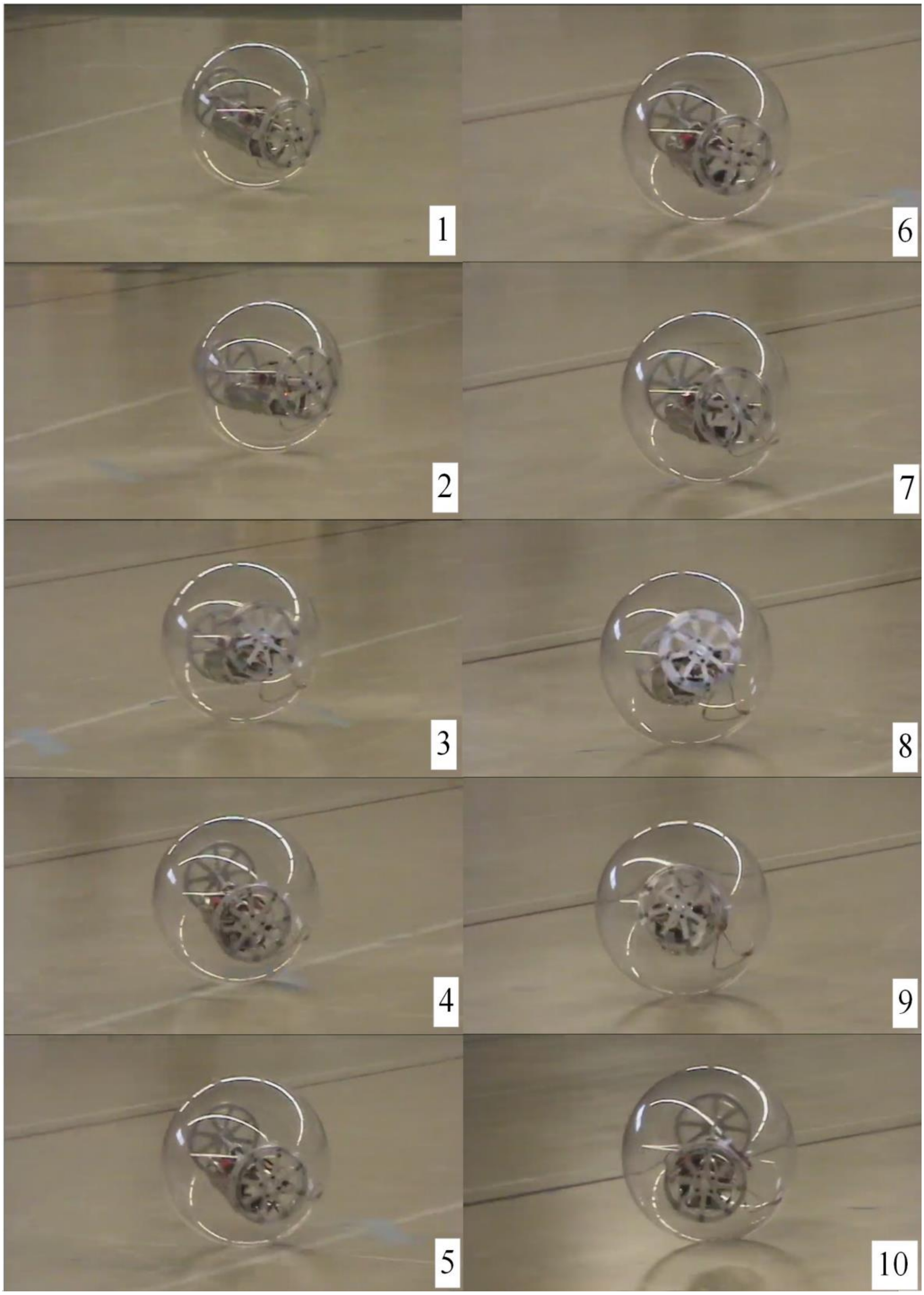


Figure 29: Video snapshots of a wobbly spherical robot (Wobble, 2013)

When we examine the movements of spherical robots, especially on 3D terrains, it is inevitable that unbalanced movements will occur even if gyroscopic stabilizers are used due to the spherical geometries of spherical robots (Moazami et al., 2019b).

It has been observed that the unbalanced movements, wobble, and skid problems are minimized in the analysis and experimental studies performed on 3D terrains with dynamic modeling of two identical coupled spherical robots.

3. MATERIAL AND METHOD

3.1. Model and Geometry

The designs of a single spherical robot and two identical coupled spherical robots were made by using Solidworks software.

3.1.1. Geometry of Spherical Robot

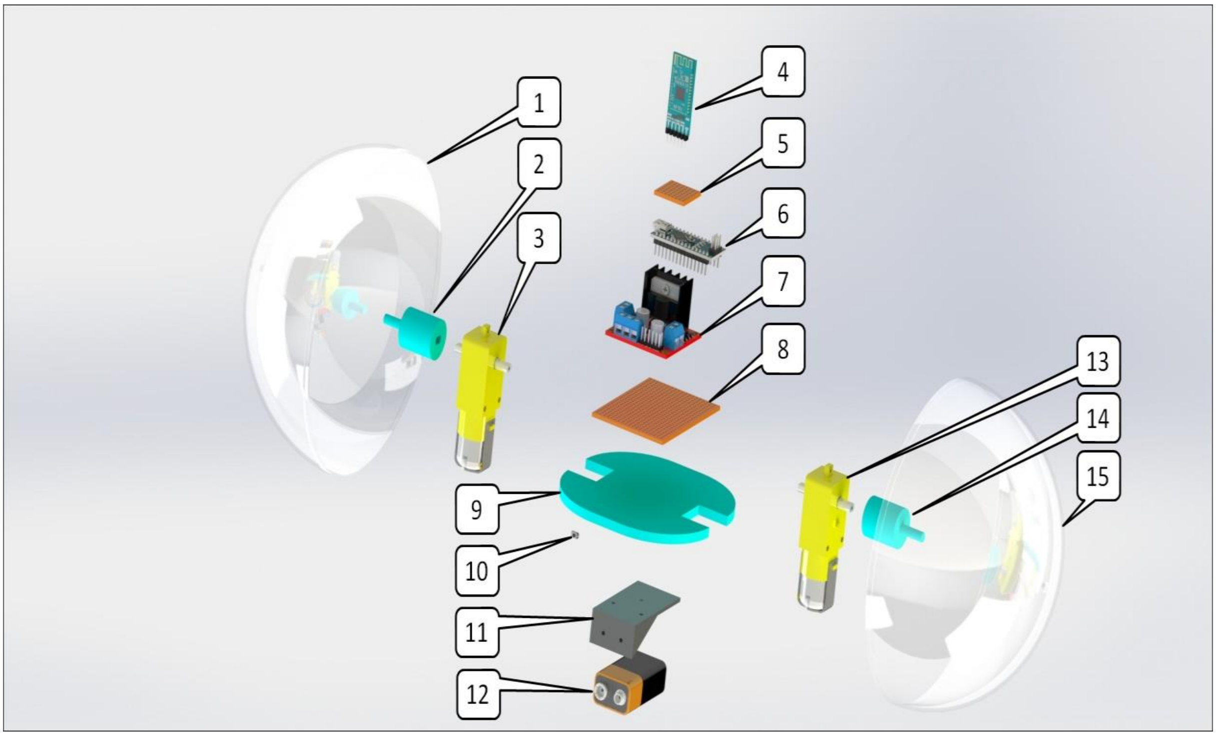


Figure 30: Design of a typical spherical robot (the radius of the spherical robot is 80 mm.)parts of spherical robot: 1&15= spherical shell (acrylic), 2&14= connector (3d print), 3&13= dc gear motor, 4= bluetooth module, 5&8 = circuit board, 6= arduino nano, 7= motordriver, 9= support plate (3d print), 10= switch, 11= battery housing, 12= 9v battery

3.1.2. Components of Spherical Robot

3.1.2.1. Acrylic Spherical Shell

160 mm openable transparent sphere. The production material is acrylic. It has an Impact resistant and low rough surface. It acts as an outer shell in this project.

Figure 31: 160 mm acrylic sphere (N11,)

3.1.2.2. Arduino Nano

The Arduino Nano is a small, complete, and breadboard friendly board based on the ATmega328 (Arduino Nano 3.x). It is preferred in small projects where more space is important (Arduino,).

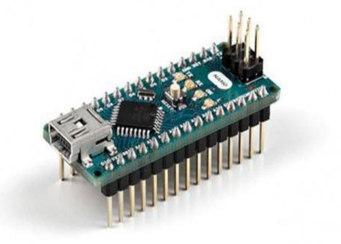


Figure 32: Arduino nano (Arduino,)

- **Memory and Specifications of Arduino Nano**

- Flash Memory of Arduino Nano is 32 kb.
- It has preinstalled bootloader on it, which takes a flash memory of 2 kb.
- Microcontroller: ATmega328
- Architecture: AVR
- Operating Voltage: 5 V
- SRAM: 2 kb
- Clock Speed: 16 MHz
- Analog IN Pins: 8
- EEPROM: 1 KB
- DC Current per I/O Pins: 40 mA (I/O Pins)
- Input Voltage: 7-12 V
- Digital I/O Pins: 22 (6 of which are PWM)
- PWM Output: 6
- Power Consumption: 19 mA
- PCB Size: 18 x 45 mm
- Weight: 7 g

• Applications of Arduino Nano

• Embedded Systems

• Automation

• Robotics

• Control Systems

• Instrumentation

• Input and Output

Each of the 14 digital pins on the Nano can be used as an input or output, using pinMode(), digitalWrite(), and digitalRead() functions. In addition, some pins have specialized functions (Arduino,).

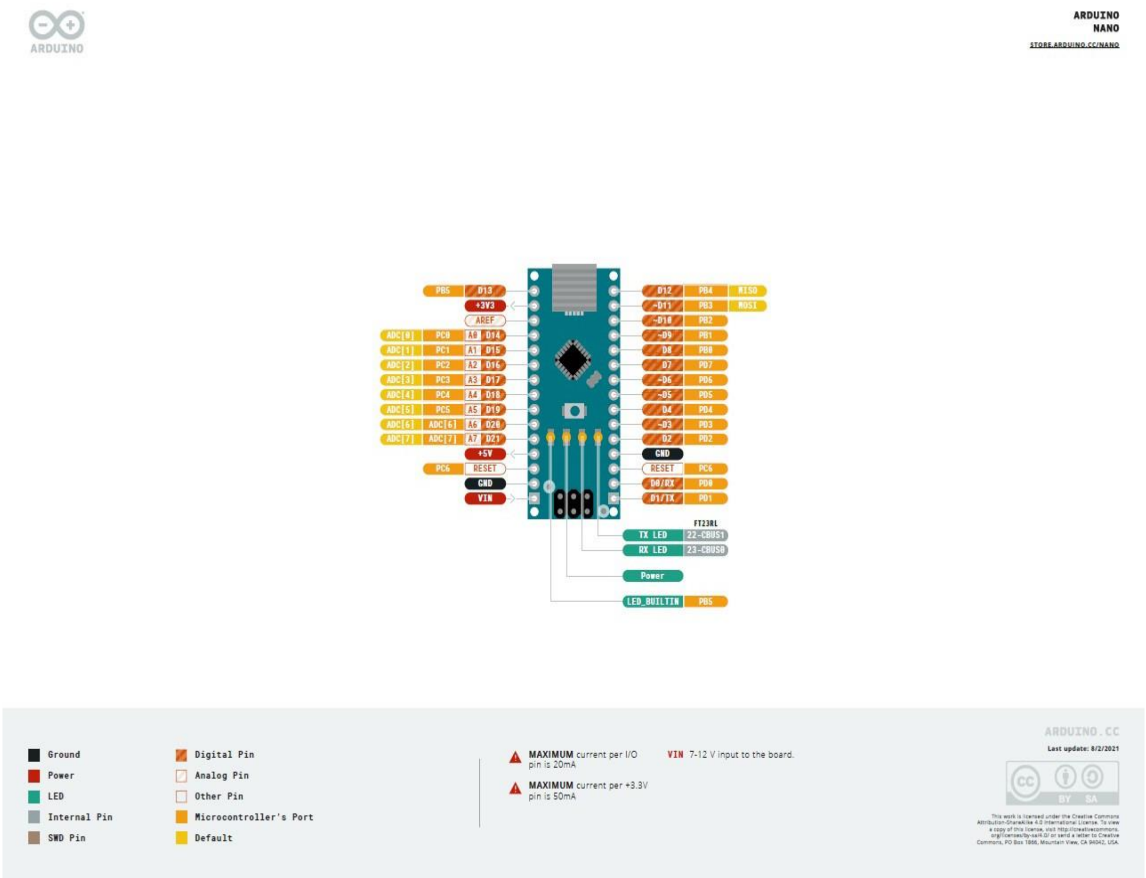


Figure 33: Pinout diagram(Arduino,)

• **Communication**

The Arduino Nano has a number of facilities for communicating with a computer, another Arduino, or other microcontrollers.

• **Programming**

The Arduino Nano can be programmed with the Arduino software (download) (Arduino,).

• **Automatic (Software) Reset**

Rather then requiring a physical press of the reset button before an upload, the Arduino Nano is designed in a way that allows it to be reset by software running on a connected computer (Arduino,).

3.1.2.3. DC Gear Motor

It consists of an electric DC motor and a gearbox or gearhead; these gearheads are used to reduce the DC motor speed while increasing the DC motor torque. Therefore the user can get the lower speed and higher torque from the gear motor (Etonm,).

Figure 34: Dc gear motor (Joom,)

Features of DC Motor:

• Operation Voltage: 3-12V

• Reduction Rate: 1:48

• Speed: 250 Rpm (@6V)

• Current: 95 mA (max. 160mA)

• Weight: 29 g (Robotistan,)

3.1.2.4. HC-05 Bluetooth Module

With HC-05 modules can be transmitted data between two HC-05 and can be also sent data from HC-05 to any Bluetooth appliance i.e. mobile phone, laptop, etc.

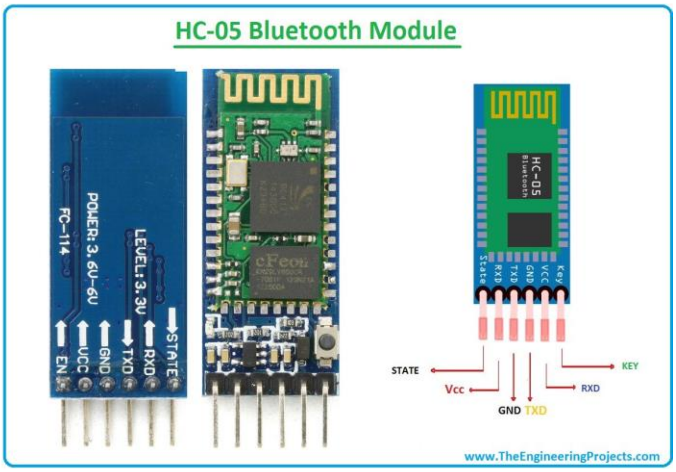


Figure 35: Hc-05 bluetooth module(Theengineeringprojects,)

Features of HC-05:

• HC05 follows the ”Bluetooth V2.0+EDR” protocol (EDR stands for Enhanced Data Rate).

• Its operating frequency is 2.4 GHz ISM Band.

• HC05 uses CSR Bluecore 04-External single-chip Bluetooth system with CMOS technology.

• It follows the IEEE (Institute of Electrical and Electronics Engineers) 802.15.1 standardprotocol.

• Dimensions of HC-05 are 12.7mmx27mm.

- Its operating voltage is 5V.
- It sends and receives data by UART, which is also used for setting the baud rate.
- It has -80dBm sensitivity.
- It also uses (FHSS), it is a technique by which a radio signal is sent at different frequency levels.
- It has the ability to work as a master/slave mode.
- It can be easily connected with a laptop or mobile phone via Bluetooth.

3.1.2.5. L298N Motor Driver

The L298N is a dual H-Bridge motor driver which allows speed and direction control of two DC motors at the same time. The module can drive DC motors that have voltages between 5 and 35V, with a peak current up to 2A (Howtomechatronics, 2017a).

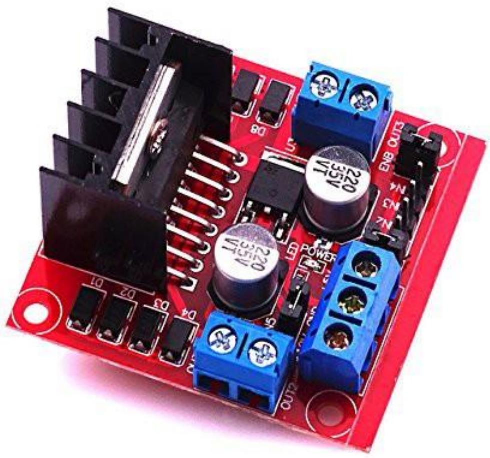


Figure 36: L298n motor driver (Amazon,)

3.1.2.6. 6LR61 Power Supply

Duracell Ultra Power batteries give you reliable high performance and long-lasting power in a broad range of everyday devices. These batteries can be used in many electronic devices.

Nominal voltage	9 V
Impedance	1,700 m-ohm @ 1 kHz
Typical weight	45 g (1.6 oz)
Typical volume	22.8 cm³ (1.4 in³)
Terminals	Miniature snap
Storage temperature range	5°C to 30°C (41°F to 86°F)
Operating temperature range	-20°C to 54°C (-4°F to 130°F)
Designation	IEC: 6LR61

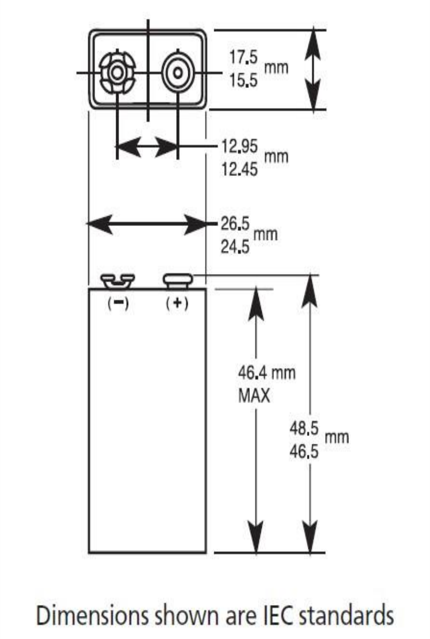


Figure 37: 6lr61 power supply(Ie.rs-online,)

3.1.2.7. Switch

A switch is a component that controls the open-ness or closed-ness of an electric circuit.

Figure 38: Slide switches(Cevikltd,)

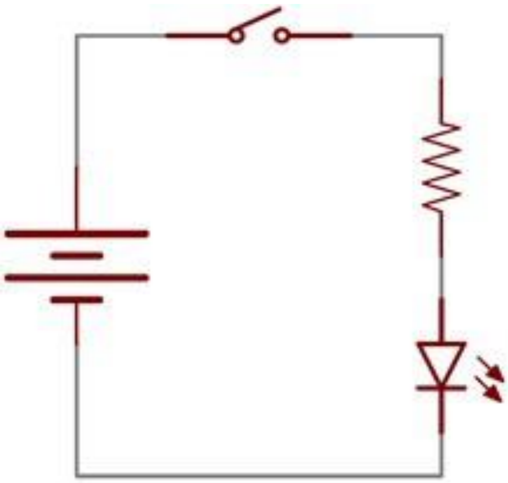


Figure 39: Basic switch circuit(Learn.sparkfun,)

3.1.2.8. 3D Printed Parts

The connectors and support plates that designed during the project were printed with a 3D printer. Raw material selections were made according to their sensitivity, strength, and usage areas.

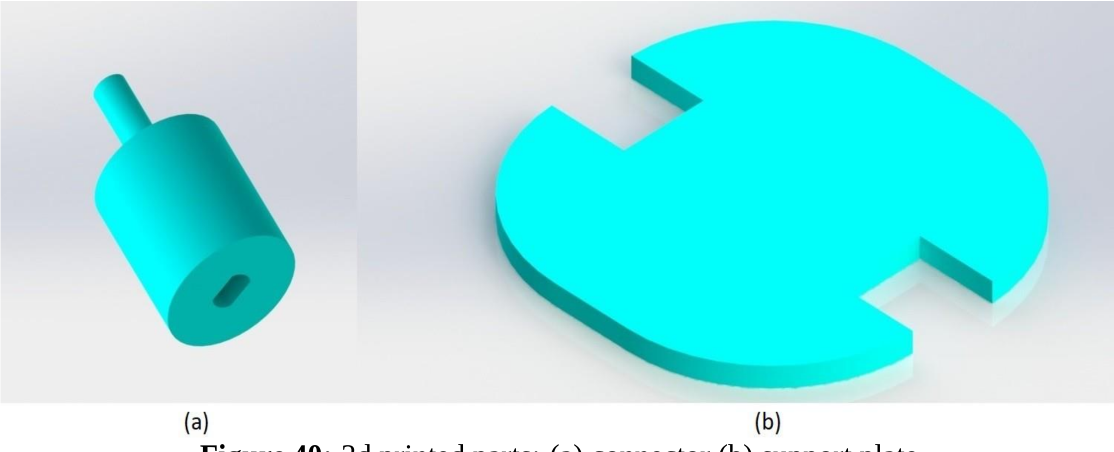


Figure 40: 3d printed parts: (a) connector (b) support plate

3.1.3. Assemble of Spherical Robot

This section includes the joining topics of the robot under construction. For individuals who want to redo the project, it is necessary to use the information in this section. Electronic Assemble

3.1.3.1. Electronic Assemble

Arduino is the base of the whole electronic part of the robot. Collects all parts as one body. The figure below shows the flowchart of the electronic part.

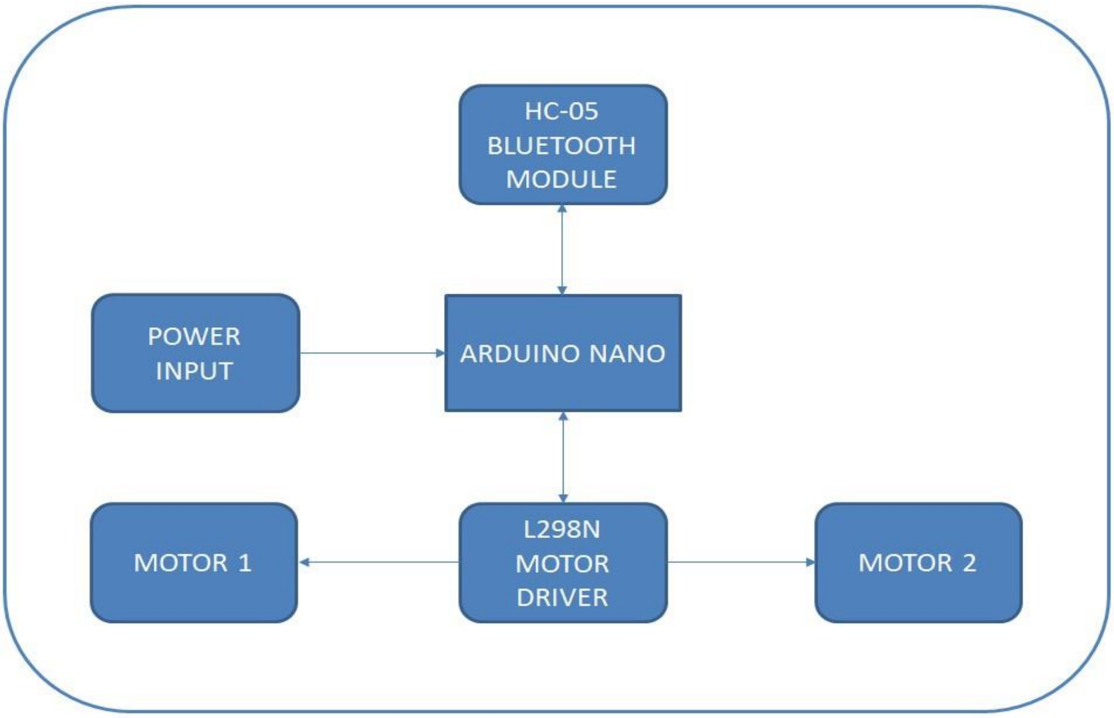


Figure 41: Flowchart of the electronic components

• **H-Bridge DC Motor Control**

Howtomechatronics team explained in detail how to control the motor rotation direction with the H-bridge.

(‘’*For controlling the rotation direction, we just need to inverse the direction of the current flow through the motor, and the most common method of doing that is by using an H-Bridge.*

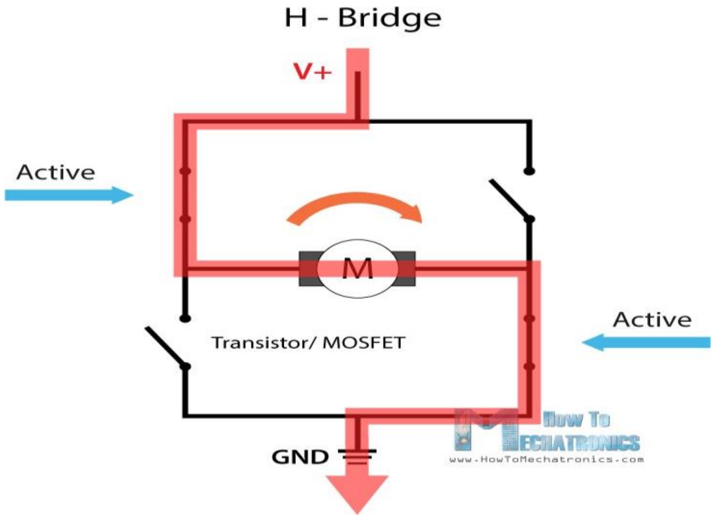


Figure 42: H-bridge (Howtomechatronics, 2017a)

Let’s take a closer look at the pinout of the L298N module and explain how it works. The module has two screw terminal blocks for motor A and B, and another screw terminal block for the Ground pin, the VCC for the motor, and a 5V pin which can either be an input or output.

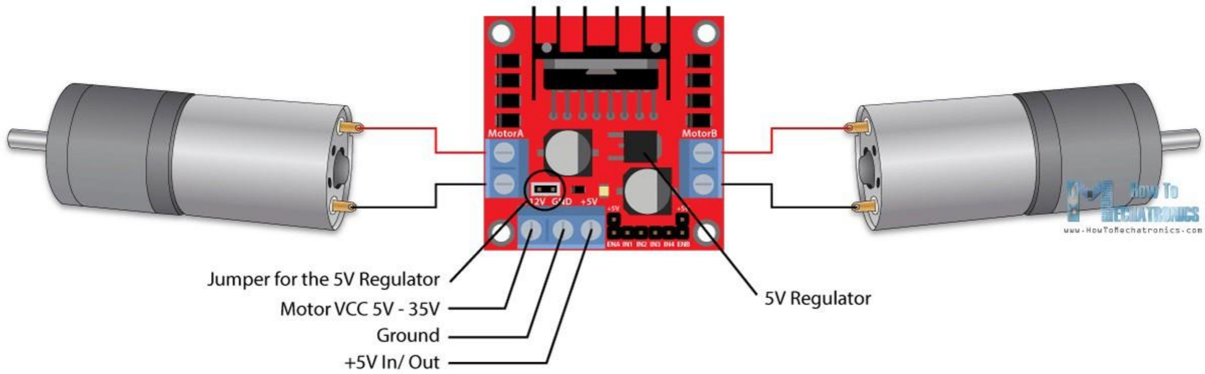


Figure 43: L298n and dc motors (Howtomechatronics, 2017a)

This depends on the voltage used at the motors VCC. The module has an onboard 5V regulator which is either enabled or disabled using a jumper. If the motor supply voltage is upto 12V we can enable the 5V regulator and the 5V pin can be used as output, for example for powering our Arduino board. But if the motor voltage is greater than 12V we must disconnect the jumper because those voltages will cause damage to the onboard 5V regulator. In this case, the 5V pin will be used as input as we need to connect it to a 5V power supply in order the IC to work properly.

We can note here that this IC makes a voltage drop of about 2V. So for example, if we use a 12V power supply, the voltage at motor terminals will be about 10V, which means that we won't be able to get the maximum speed out of our 12V DC motor.

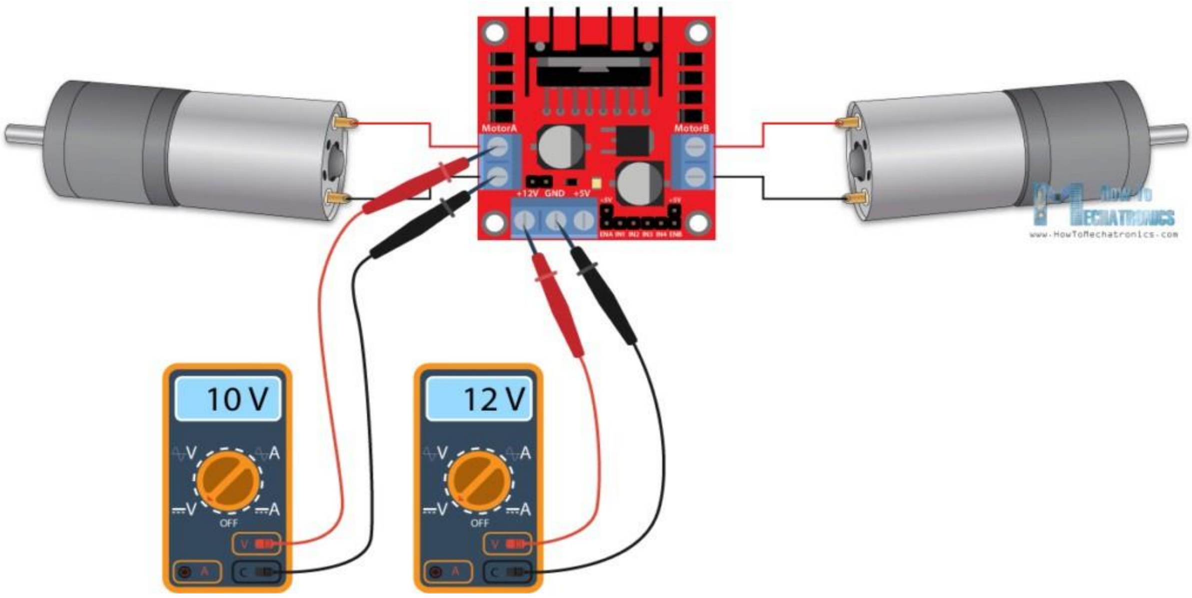


Figure 44: L298n and dc motors (Voltage Drop)(Howtomechatronics, 2017a)

Next are the logic control inputs. The Enable A and Enable B pins are used for enabling and controlling the speed of the motor. If a jumper is present on this pin, the motor will be enabled and work at maximum speed, and if we remove the jumper we can connect a PWM input to this pin and in that way control the speed of the motor. If we connect this pin to a Ground the motor will be disabled.

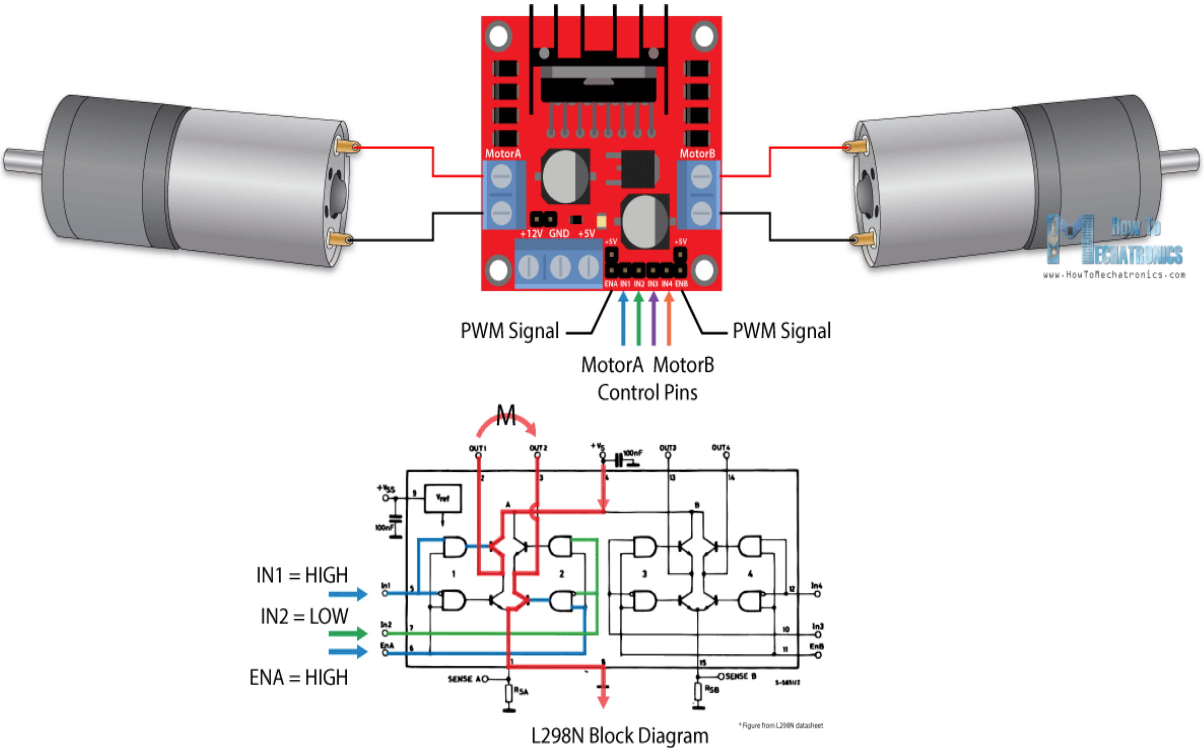


Figure 45: L298n block diagram (Howtomechatronics, 2017a)

Next, the Input 1 and Input 2 pins are used for controlling the rotation direction of motor A, and the inputs 3 and 4 for motor B. Using these pins we actually control the switches of the H-Bridge inside the L298N IC. If input 1 is LOW and input 2 is HIGH the motor will move forward, and vice versa, if input 1 is HIGH and input 2 is LOW the motor will move backward. In case both inputs are the same, either LOW or HIGH the motor will stop. The same applies to inputs 3 and 4 and motor B.'') (Howtomechatronics, 2017a).

• **Circuit Diagram of Spherical Robot**

Fritzing program is used to set up our Arduino system. Also, we can easily check the system working conditions. If we have a mistake with the electrical part, the program immediately finds the error. The electrical connections are shown in the figure below.

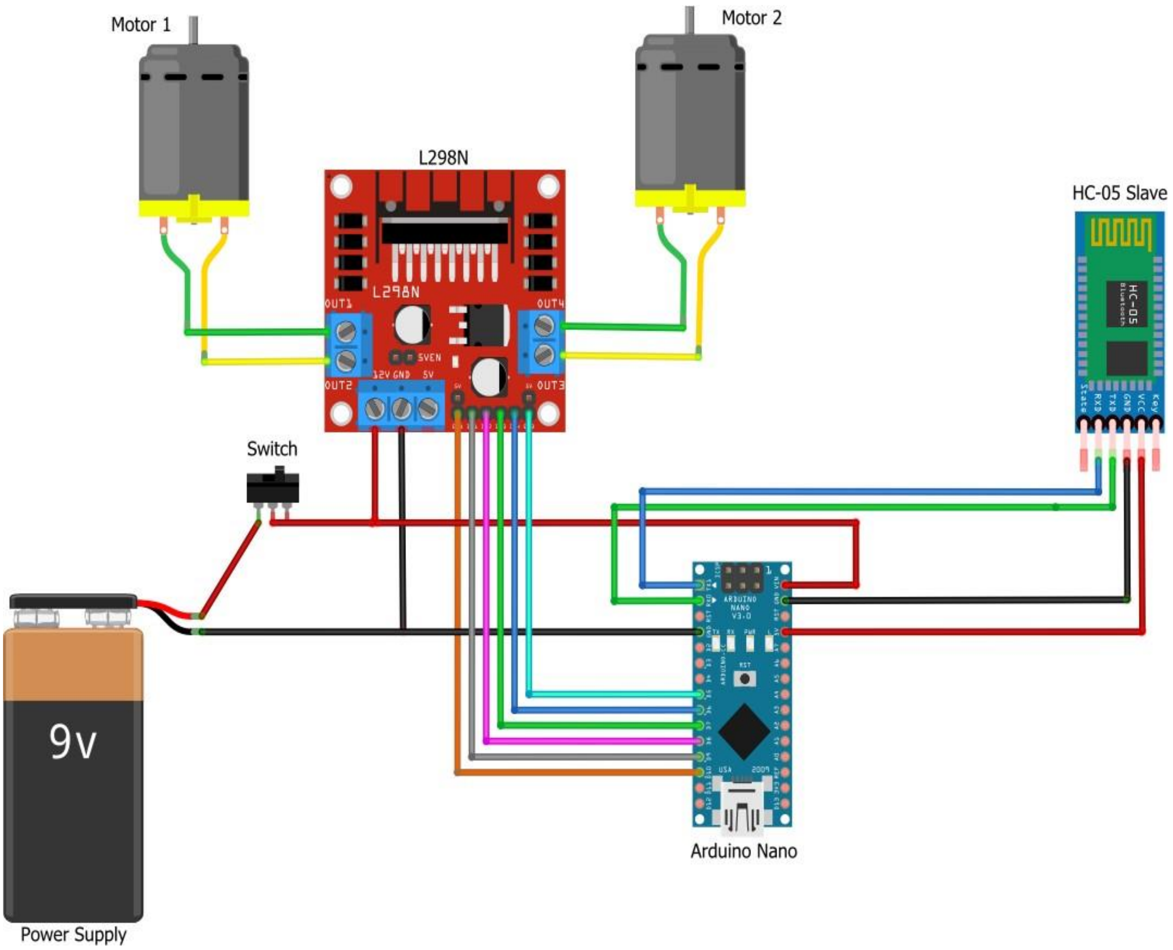


Figure 46: Circuit diagram of spherical robot

3.1.3.2. Mechanical Assemble

The part we called a base plate and connection parts have been printed in a 3D printer. All parts are collected as one solid body. Firstly, Motors are fixed to sides at their equilibrium positions. The base plate center is decided as a centroid of the whole system. Secondly, Arduino Nano, Motor Driver, and BlueTooth Module are soldered and fixed on an external wood plate. This plate's center of mass is identified and constrained to the main base plate center of mass. Motor wires are connected to the L298N Motor Driver. Thirdly, the power source is fixed to the base plate from the bottom center of the mass. Moreover, the on/off switch is soldered to the power supply and attached to the front side of the base plate with hot silicone. Finally, the out surfaces of the acrylic spherical shell are drilled from the center with a 5 mm diameter. The connection parts that printedin a 3D printer are plug into the shaft of both dc motors. The outer surfaces of connections parts are put together to the inside surface of the acrylic spherical shell with hot silicone.

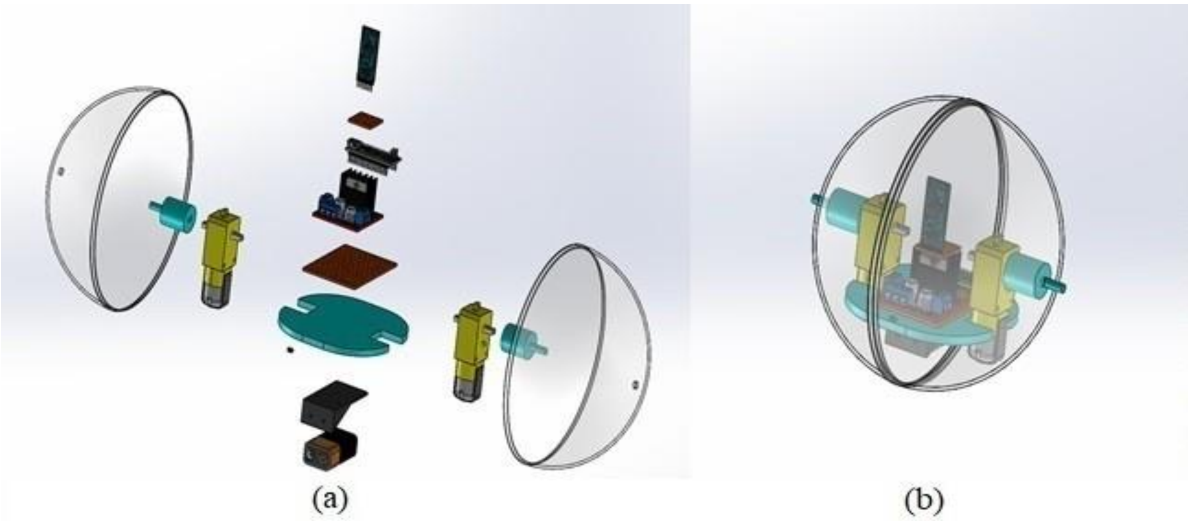


Figure 47: (a) Exploding view of spherical robot (b) assembled view of spherical robot

Picture 1: Produced spherical robots

3.1.4. Simultaneous Control of Two Identical Coupled Spherical Robots

In order to simultaneously control the two identical spherical robots, remote control with a joystick was designed. With this remote control, we can control spherical robots separately as well as at the same time.

So as to simultaneously control, four HC-05 Bluetooth Modules were used which need to be configured as master and slave devices. That was done by using AT commands. HC-05 Bluetooth Modules that in the joystick were set to be master and HC-05 Bluetooth Modules that in Spherical Robots to be slaves.

Required codes for AT commands and control of Spherical Robot are given in the appendices.

3.1.4.1. Circuit Diagram of Remote Control with a Joystick

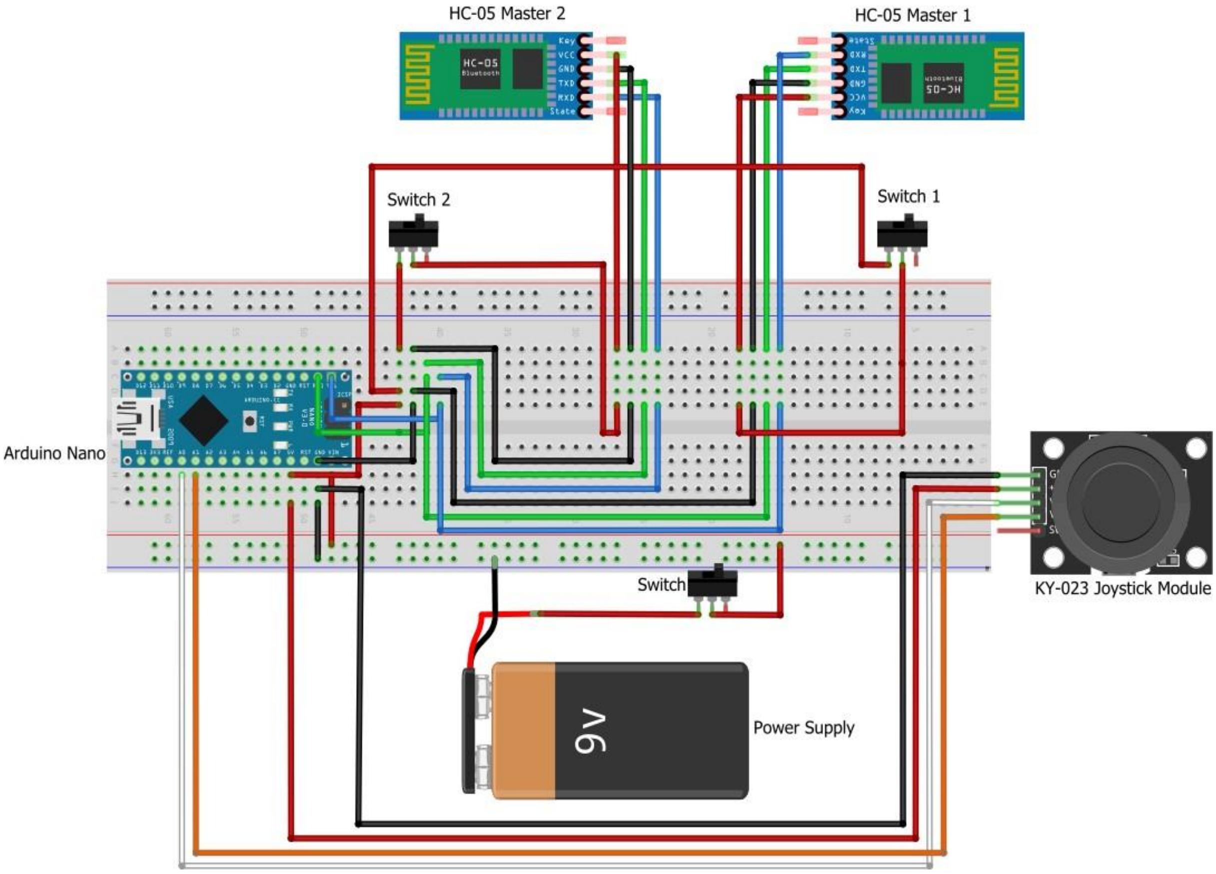
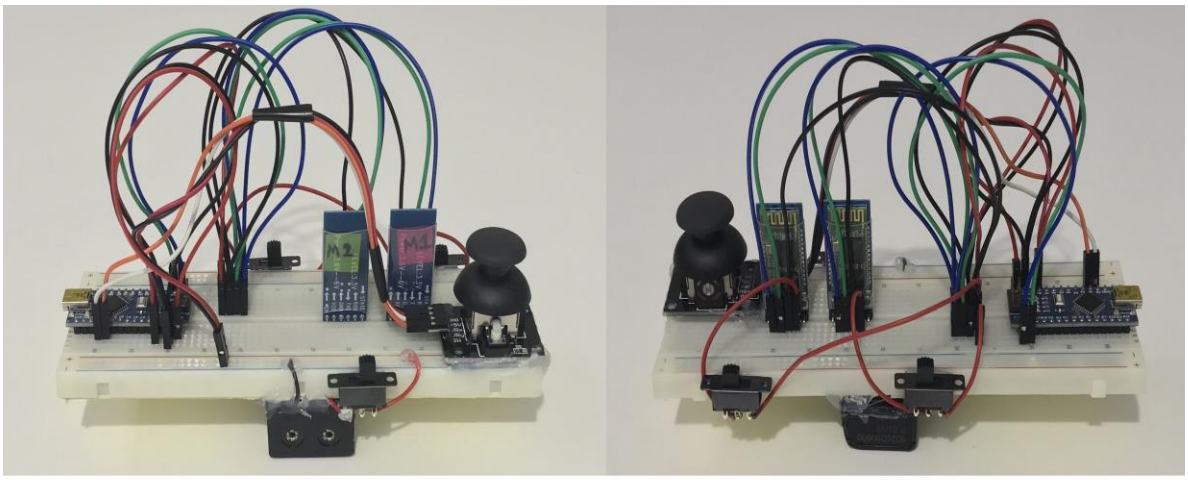


Figure 48: Circuit diagram of remote control with a joystick



(a) (b)

Picture 2: Remote control with a joystick (a) front (b) back

3.1.5. Adams Models of Two Identical Coupled Spherical Robots

We designed three different models for dynamic modeling of two identical coupled spherical robots. These are with shaft connection, with torsional soft spring connection, and with torsional stiff spring connection.

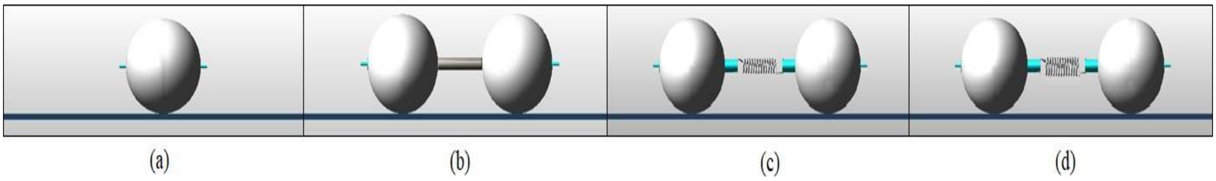


Figure 49: Simulation models: (a) single spherical robot (b) two identical coupled spherical robots which with shaft connection (c) two identical coupled spherical robots which with torsional soft spring connection (k_t =0.002 N.m/rad) (d) two identical coupled spherical robots which with torsional stiff spring connection (k_t =2 N.m/rad)

3.2. Dynamic Analysis

In total, 60 dynamic analyses which in 5 different road profiles, 4 kinds of simulation models, and 3 different speeds were made. The maximum speed of DC Gearmotors that we use is 250 rpm.When we change it to rad/sec, it will be nr_{max}=26.1799 rad/sec. (1 rpm=2π/60 rad/sec). Therefore, in view of the fact that the maximum speed of DC Gear motors, the analyses were made at three different angular velocities 6, 16 and 26 rad/sec.

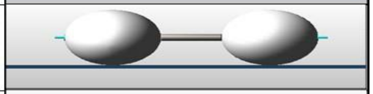
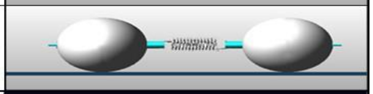
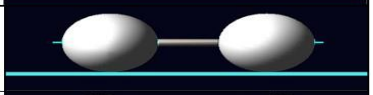
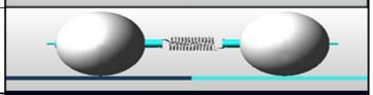
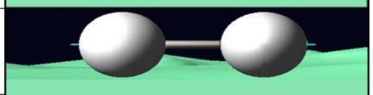
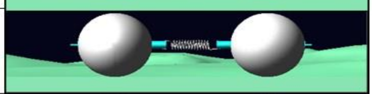
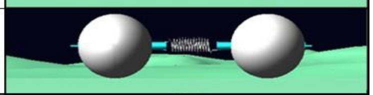
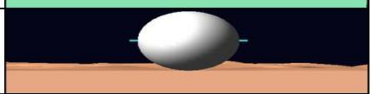
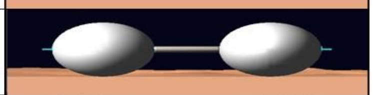
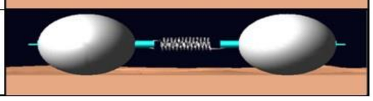
ROAD PROFILES		ANALYSIS NUMBERS	SIMULATION MODELS (Figure 49)
FLAT ROADS	ASPHALT ROAD	1st	
		2nd	
		3rd	
		4th	
	ICY ROAD	5th	
		6th	
		7th	
		8th	
	DUAL ROAD (ASPHALT&ICY)	9th	
		10th	
		11th	
		12th	
RANDOM ROADS	FIRST RANDOM SHAPED ROAD	13th	
		14th	
		15th	
		16th	
	SECOND RANDOM SHAPED ROAD	17th	
		18th	
		19th	
		20th	

Figure 50: List of dynamic analyses

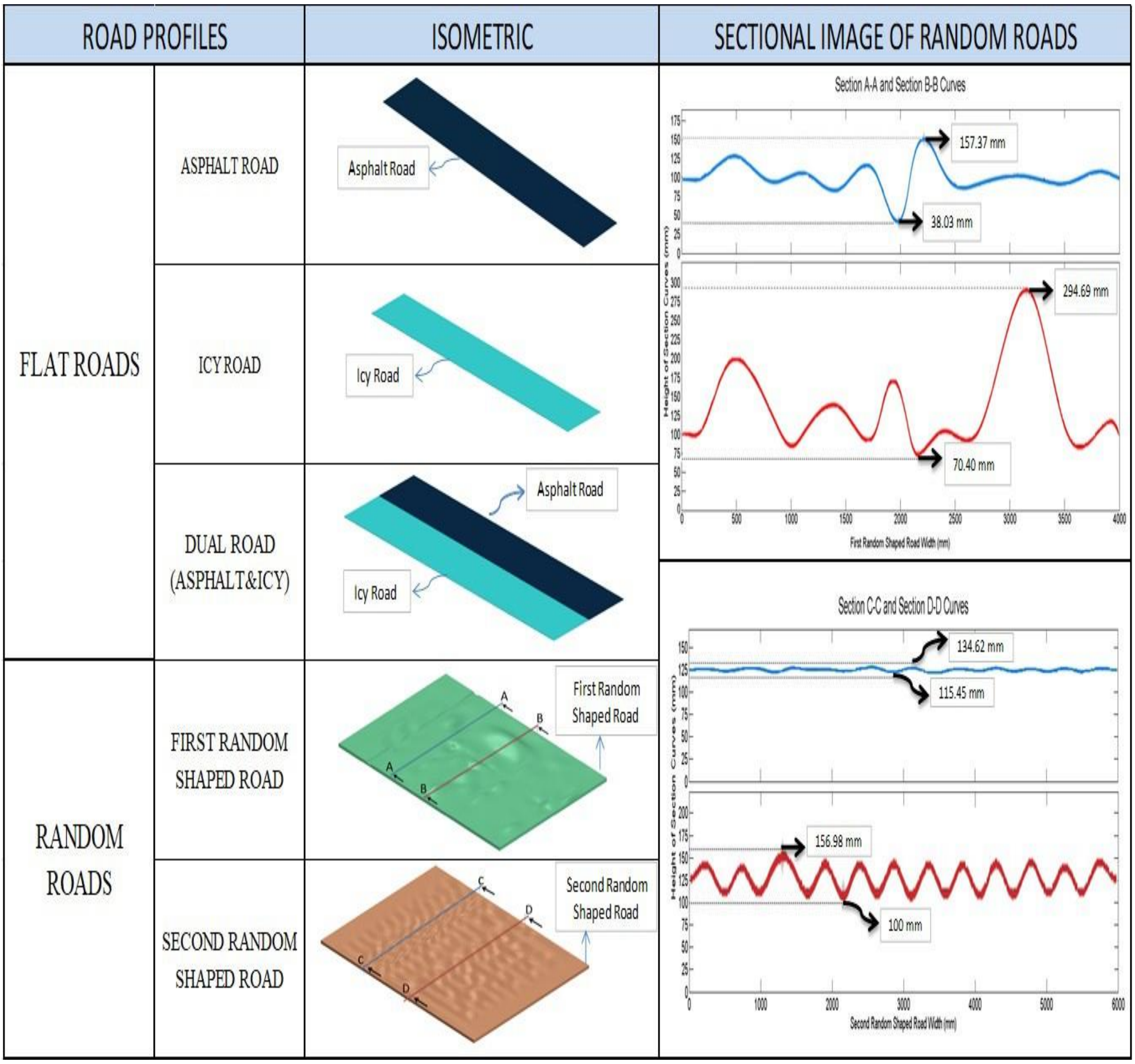


Figure 51: Road profiles

Friction coefficients $k_{asphalt,random}$=1 and k_{icy}=0.2 were chosen for asphalt,random shaped and icy roads.

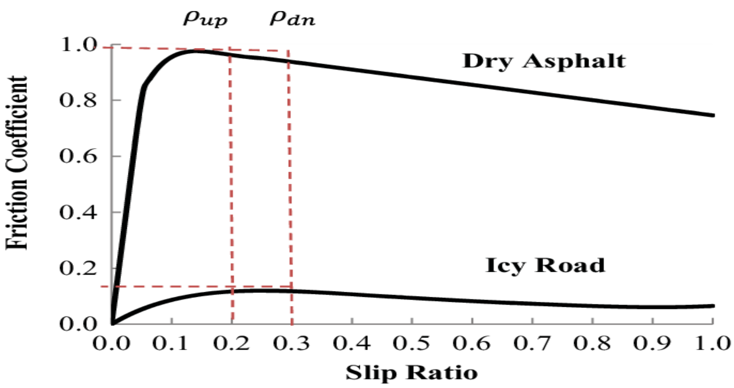


Figure 52: Friction coefficient for dry asphalt and icy road (Heerwan and Ogino, 2014)

3.2.1. Verification of Analysis

When we examine the motion of an object when it rolls on the plane without slipping, we see that the contact point of the object with the plane does not move.

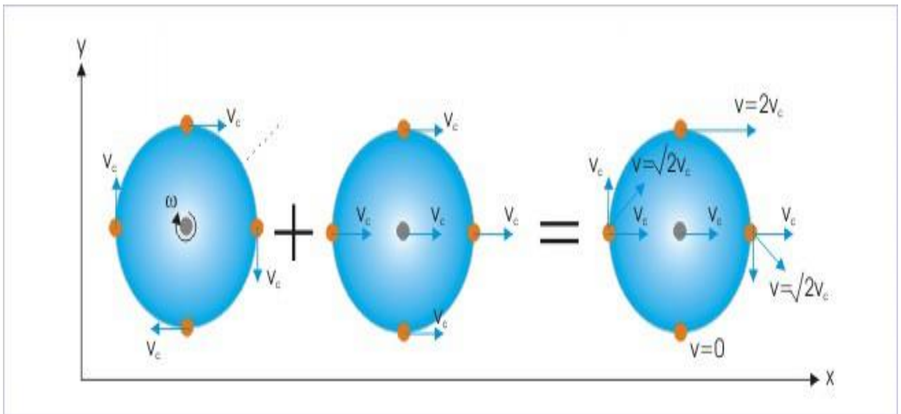


Figure 53: Rolling motion: rolling motion is a combination of rotational and translational motion. (Singh, 2011)

You can view the derivation of the equation between angular velocity, linear velocity, and radius here (Singh, 2011).

$$v = R \times \omega \tag{1}$$

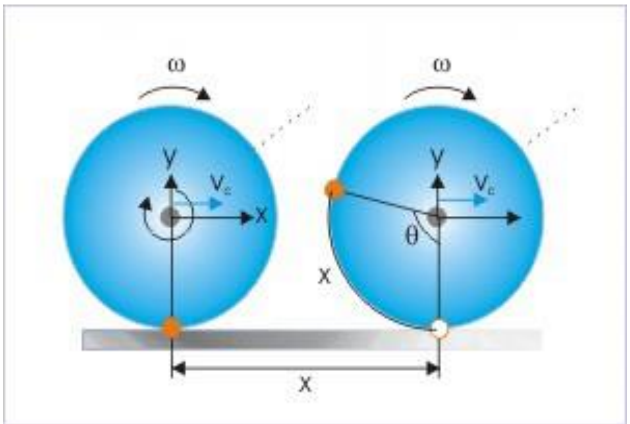


Figure 54: Rolling without slipping: a body rolling a distance of x on a plane without slipping. (Singh, 2011)

The condition for rolling without skidding is that the speeds on the contact point are zero. As seen in equation 1 the ratio of the linear velocity of the center of the sphere and the angular velocityof the sphere has to give the radius of the sphere.

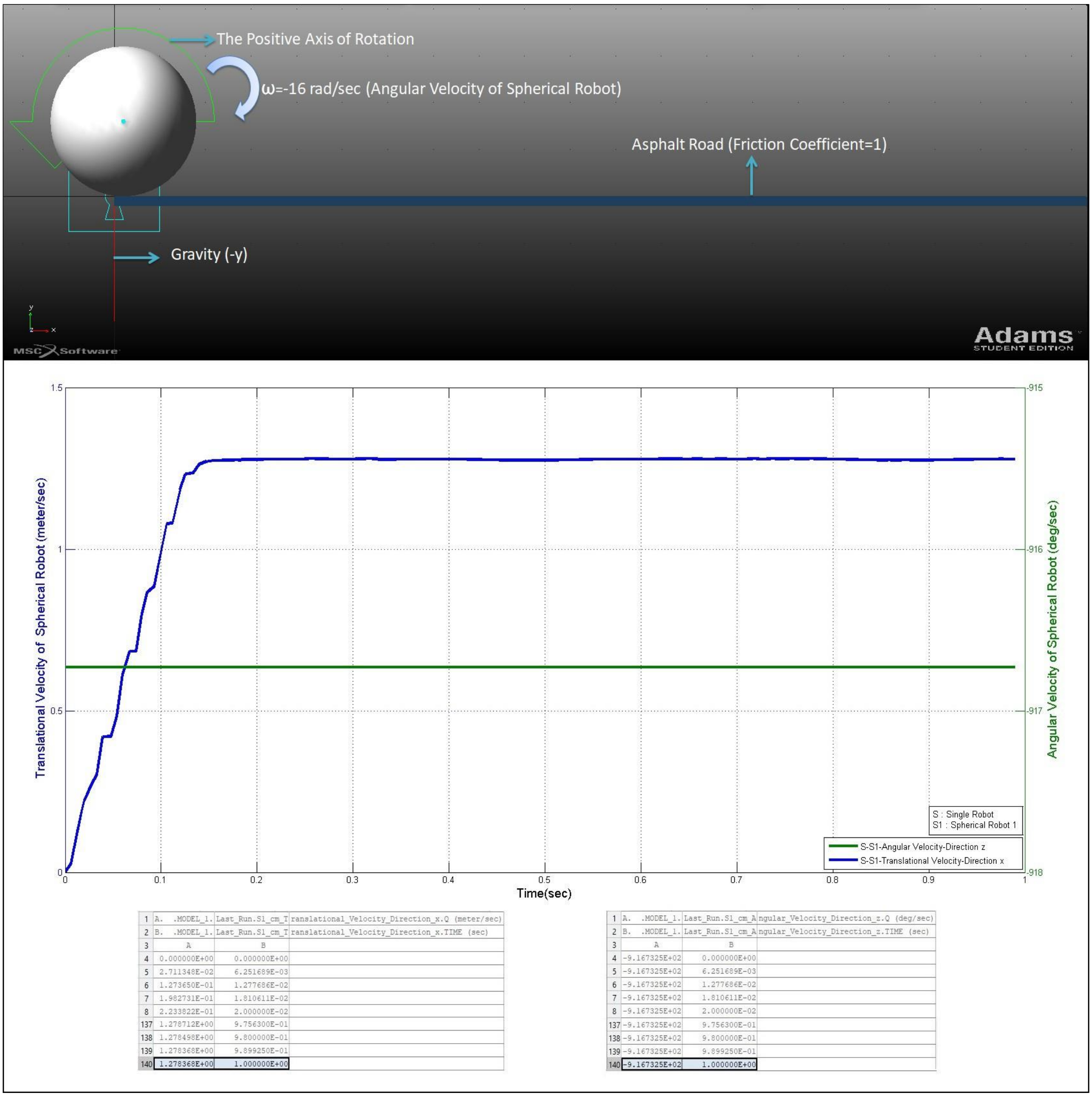


Figure 55: Translational and Angular Velocity Values in The First Second in order to Verify of Analysis

ω = 916.7325 (deg/sec) × (2π/360) ω ≈ 16 (rad/sec)

v = 1.278368 (m/sec) R = v / ω = 1.278368 / 16 = 0.079898 (m)

R = 79.898 (mm)

The radius of our spherical robot is 80 mm. Because of the friction coefficient, there is a little difference. This result shows the accuracy of the analysis.

3.3. Experimental Studies

The experiments were carried out on three different road profiles.

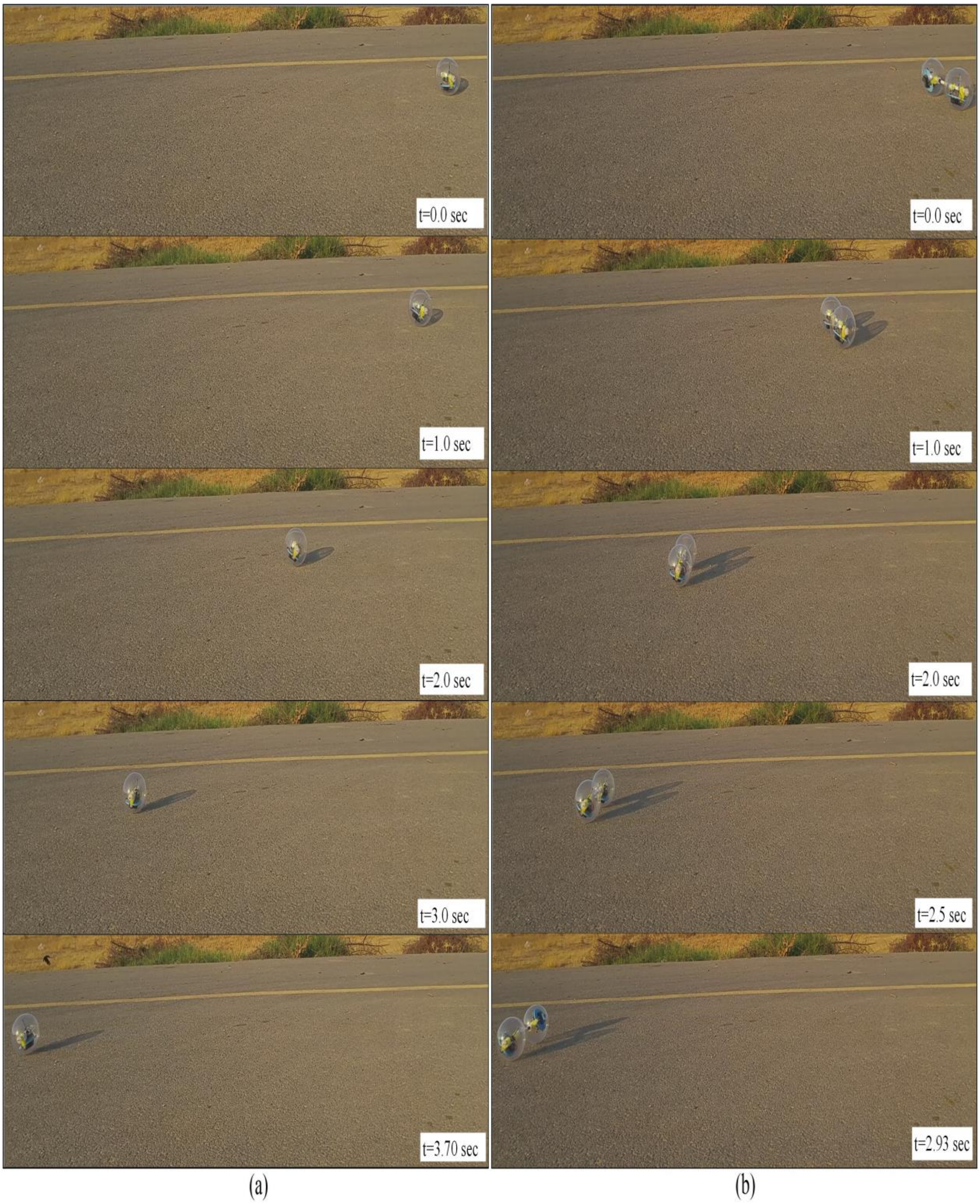


Figure 56: Video snapshots of asphalt road experiments (side) (a) single spherical robot (b) two ıdentical coupled spherical robots which with shaft connection

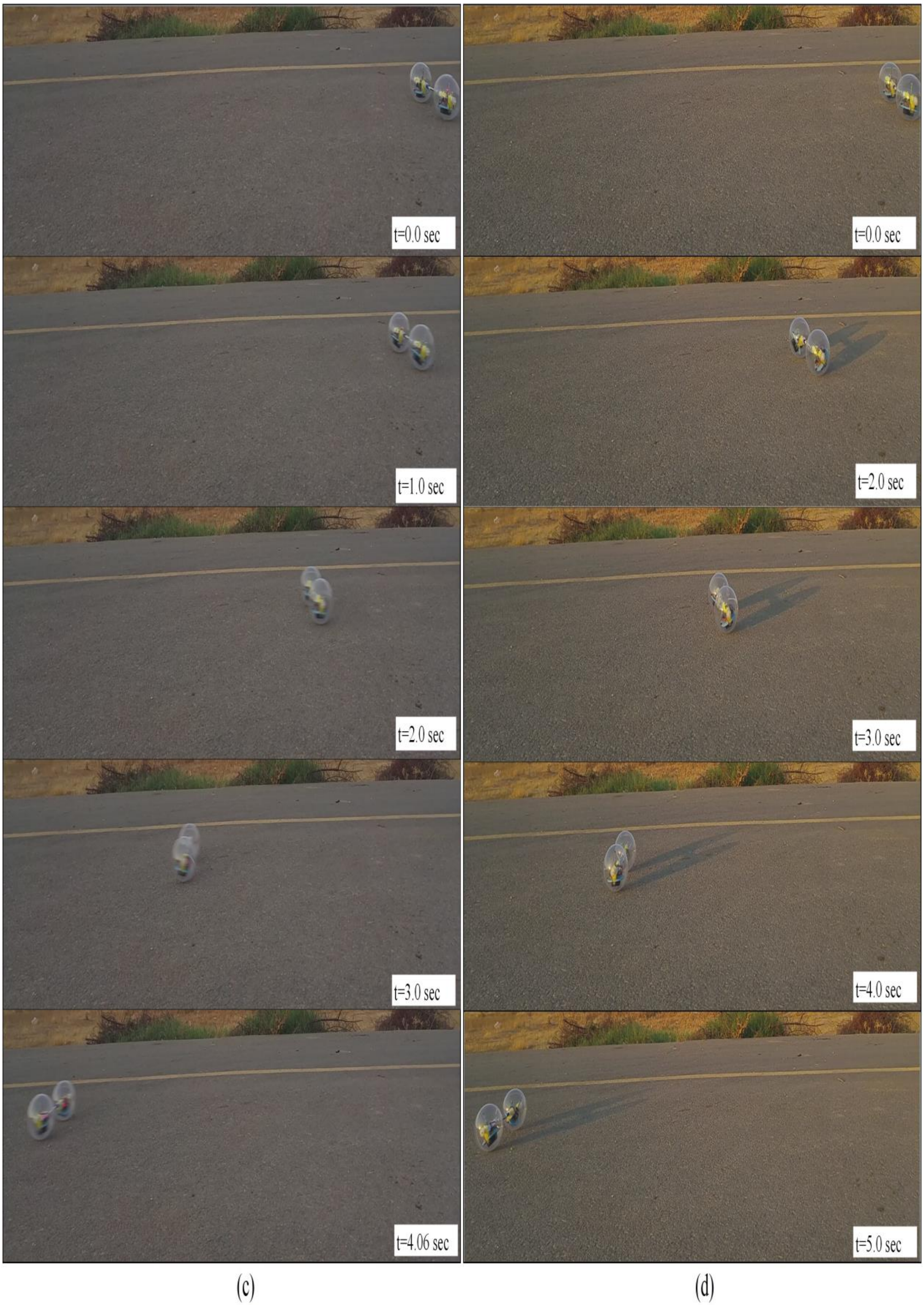


Figure 57: Video snapshots of asphalt road experiments (side) (c) two identical coupled spherical robots which with torsional soft spring connection (d) two identical coupled spherical robots which with torsional stiff spring connection

Figure 58: Video snapshots of first random road experiments (side) (a) single spherical robot (b) two identical coupled spherical robots which with shaft connection

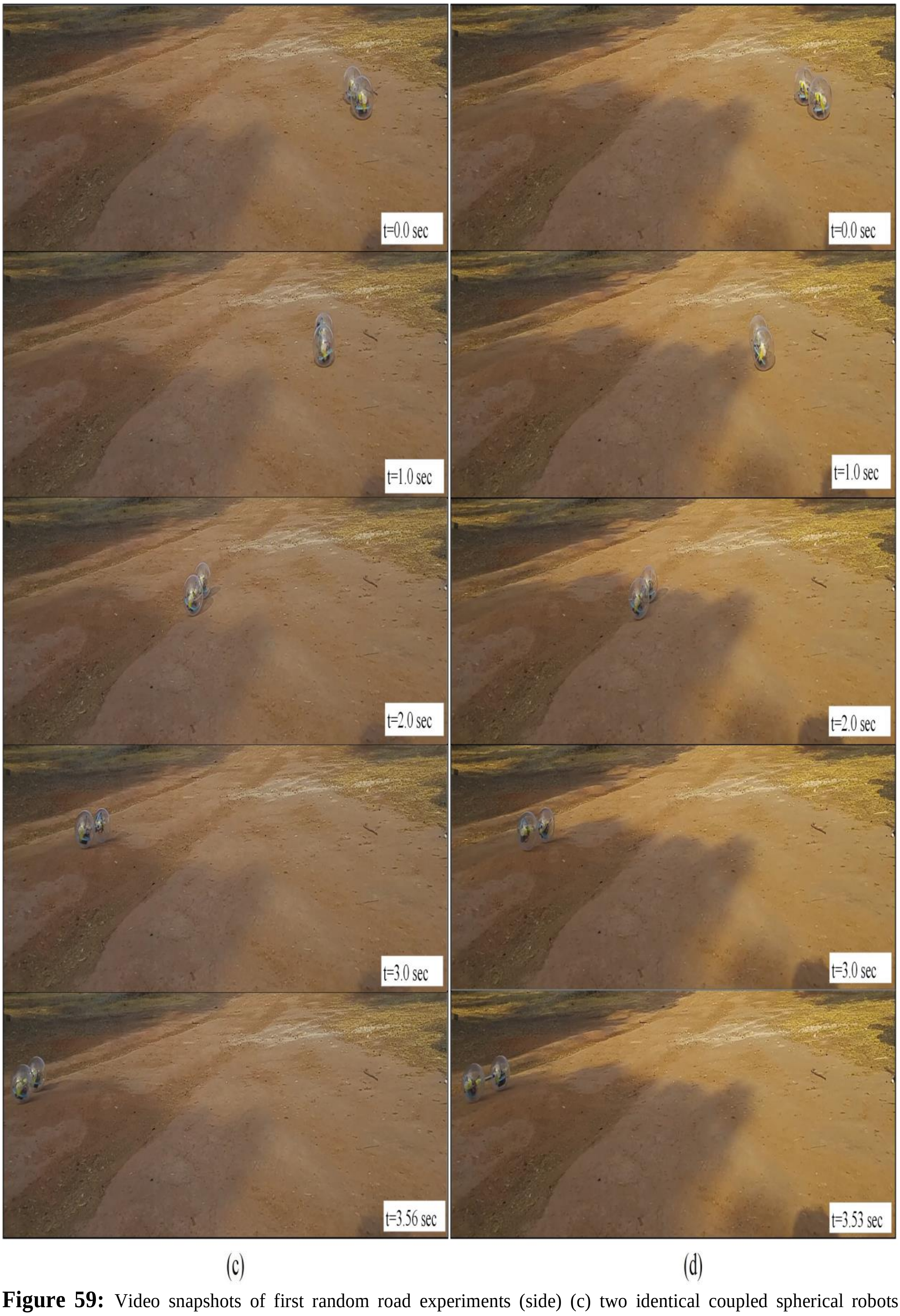


Figure 59: Video snapshots of first random road experiments (side) (c) two identical coupled spherical robots which with torsional soft spring connection (d) two identical coupled spherical robots which withtorsional stiff spring connection

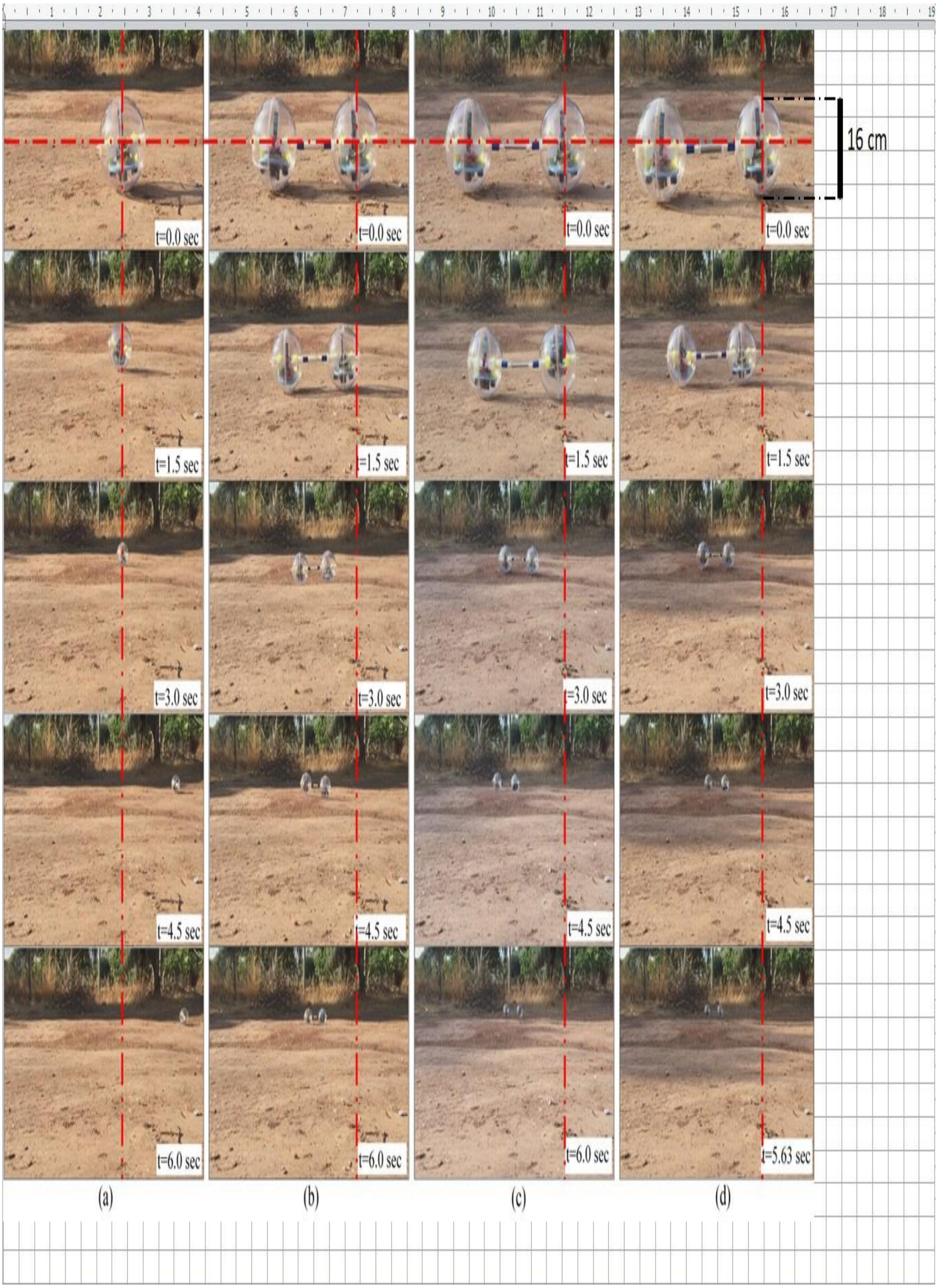


Figure 60: Video snapshots of first random road experiments (front) (a) single spherical robot (b) two identical coupled spherical robots which with shaft connection (c) two identical coupled spherical robots which with torsional soft spring connection (d) two identical coupled spherical robots which with torsionalstiff spring connection

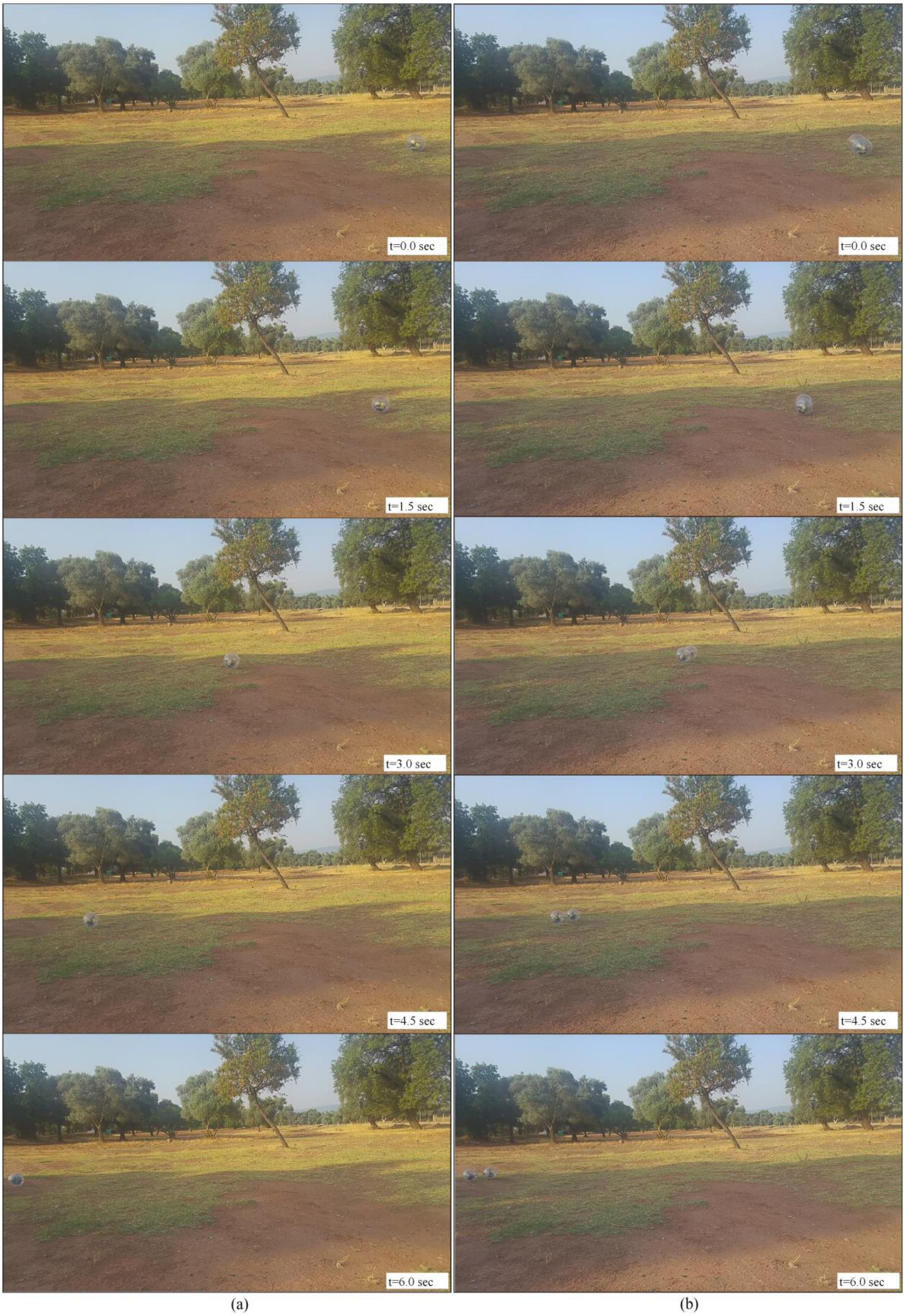


Figure 61: Video snapshots of second random road experiments (side) (a) single spherical robot (b) two identical coupled spherical robots which with shaft connection

Figure 62: Video snapshots of second random road experiments (side) (c) two identical coupled spherical robots which with torsional soft spring connection (d) two identical coupled spherical robots which with torsional stiff spring connection

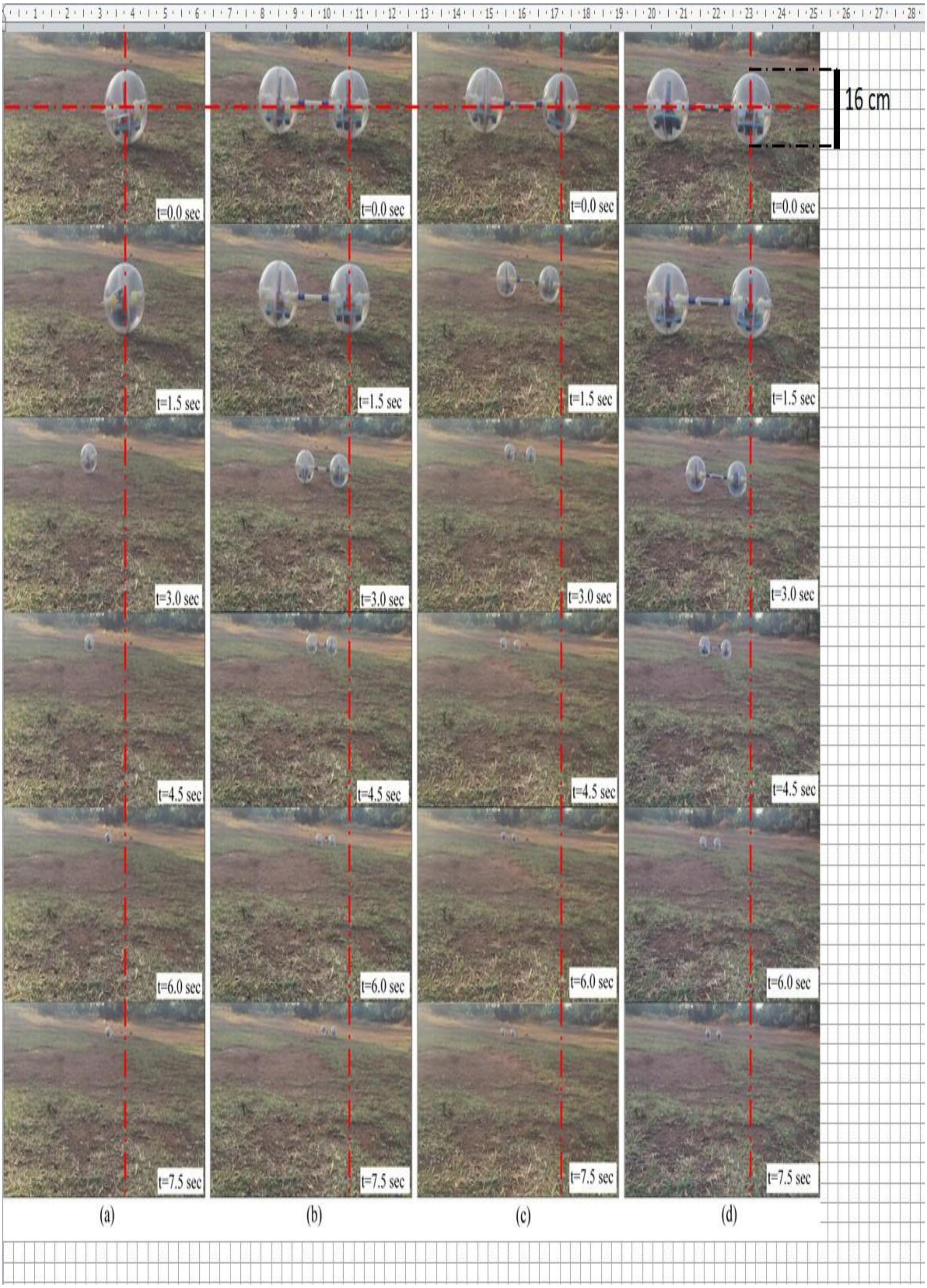


Figure 63: Video snapshots of second random road experiments (front) (a) single spherical robot (b) two identical coupled spherical robots which with shaft connection (c) two identical coupled spherical robots which with torsional soft spring connection (d) two identical coupled spherical robots which with torsionalstiff spring connection

4. RESULTS AND DISCUSSION

4.1. Flat Asphalt and Icy Roads Analyses Data

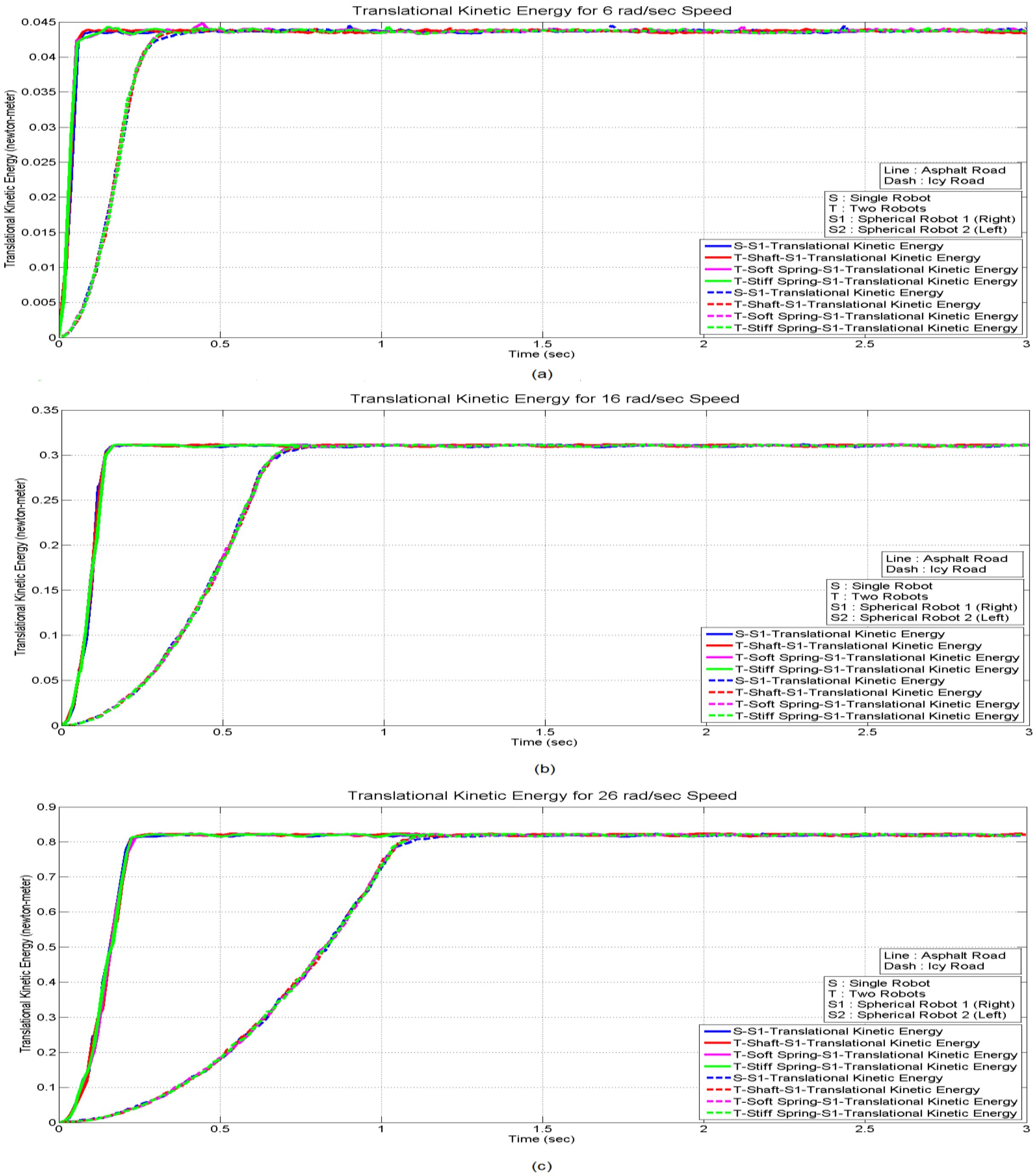
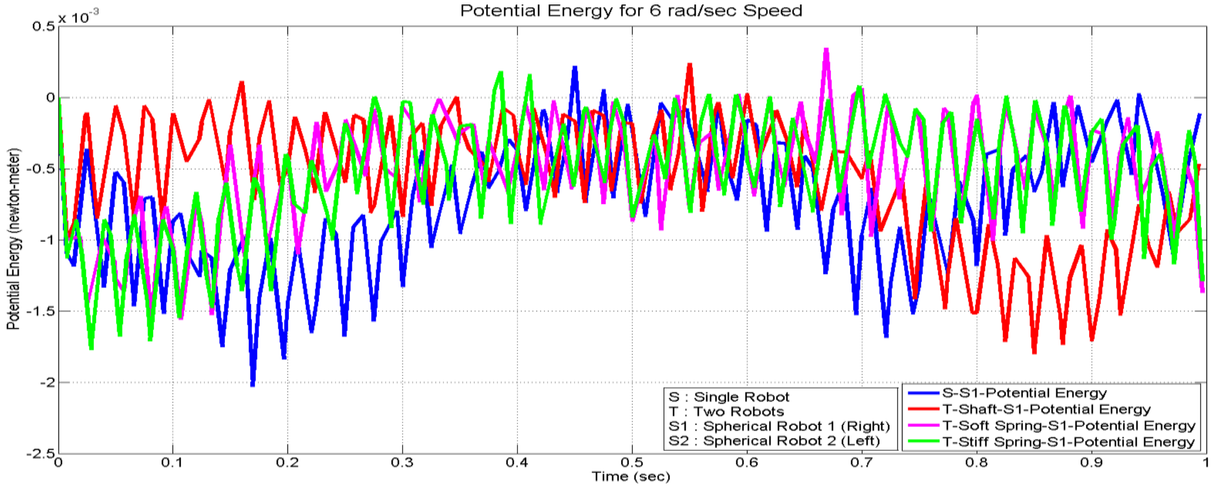
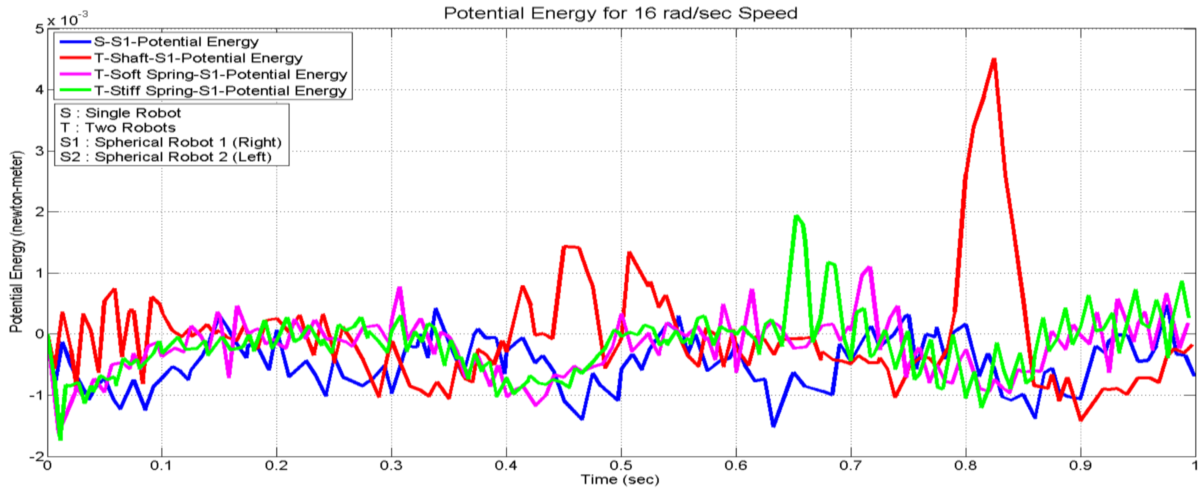


Figure 64: Translational kinetic energy for flat asphalt and icy road (a) for 6 rad/sec (b) for 16 rad/sec (c) for 26 rad/sec

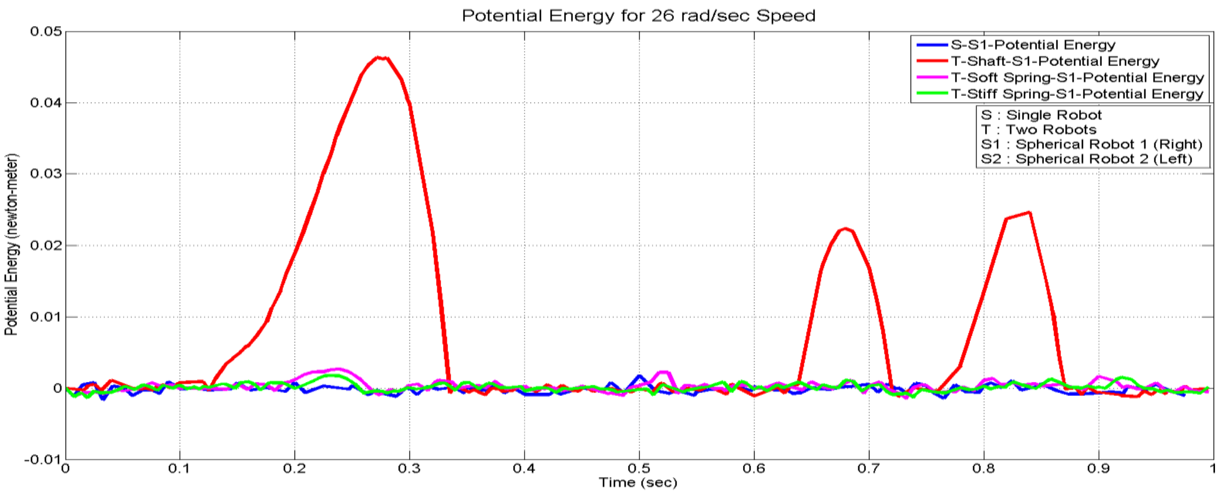
4.2. Dual (Asphalt and Icy) Flat Road Analyses Data



(a)

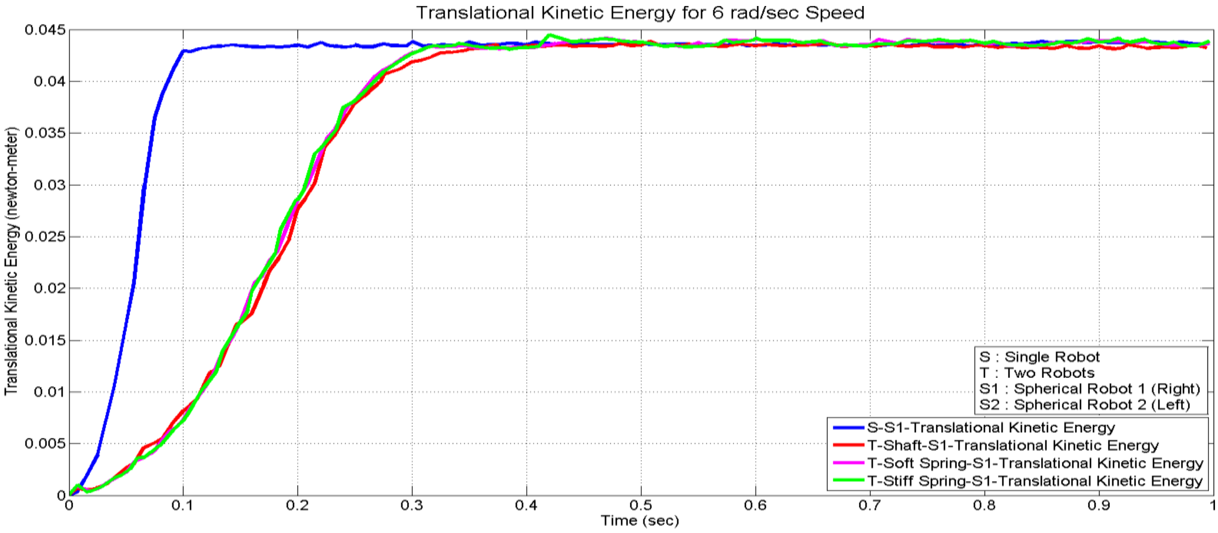


(b)

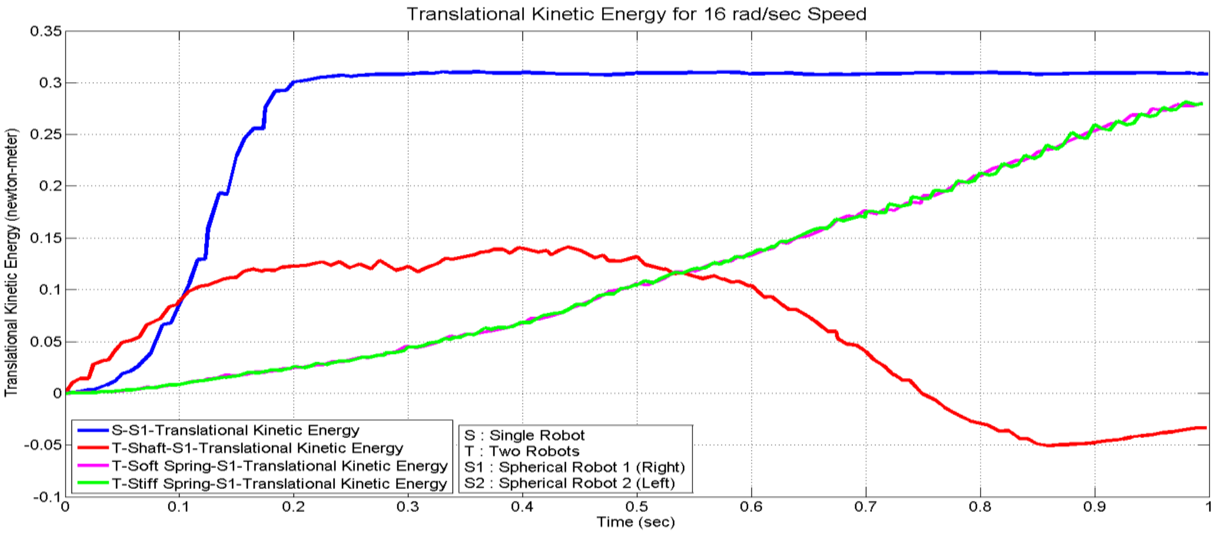


(c)

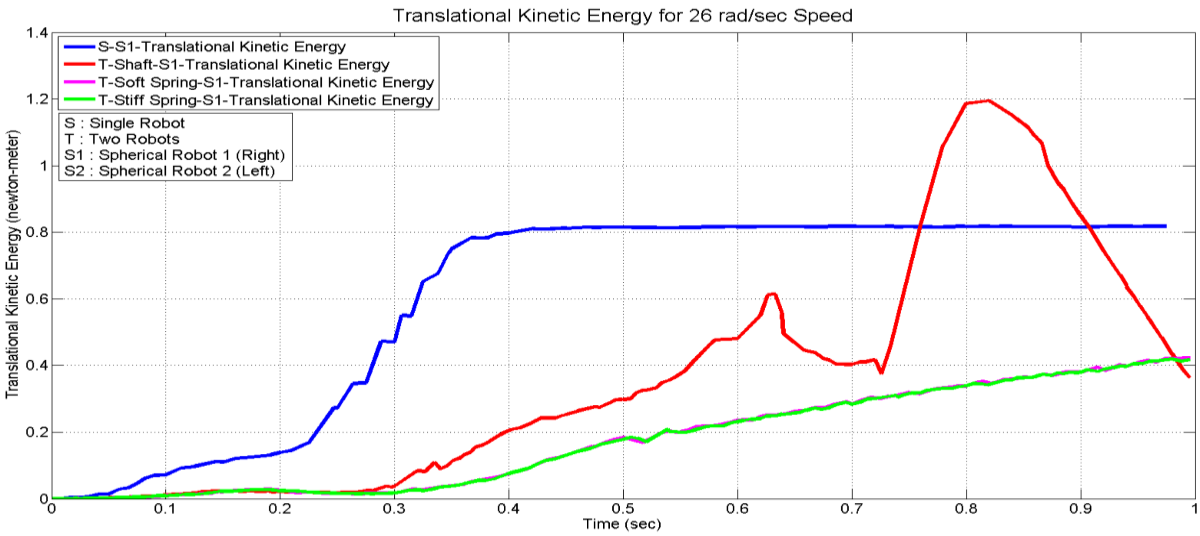
Figure 65: Potential energy for dual (asphalt and icy) flat road (a) for 6 rad/sec (b) for 16 rad/sec (c) for 26rad/sec



(a)



(b)



(c)

Figure 66: Translational kinetic energy for dual (asphalt and icy) flat road (a) for 6 rad/sec (b) for 16 rad/sec (c) for 26 rad/sec

4.3. First Random Shaped Road Analyses Data

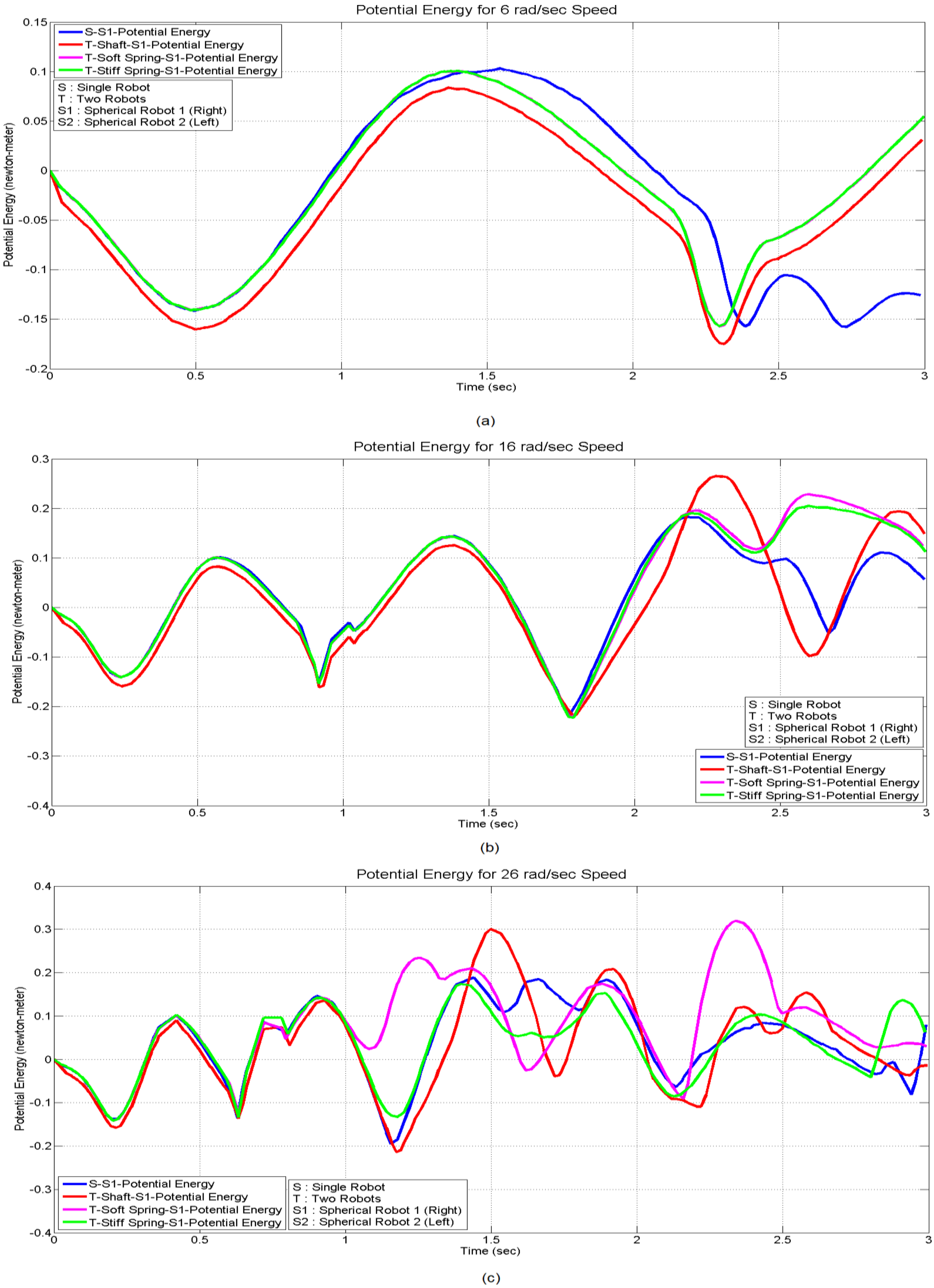


Figure 67: Potential energy for first random shaped road (a) for 6 rad/sec (b) for 16 rad/sec (c) for 26 rad/sec

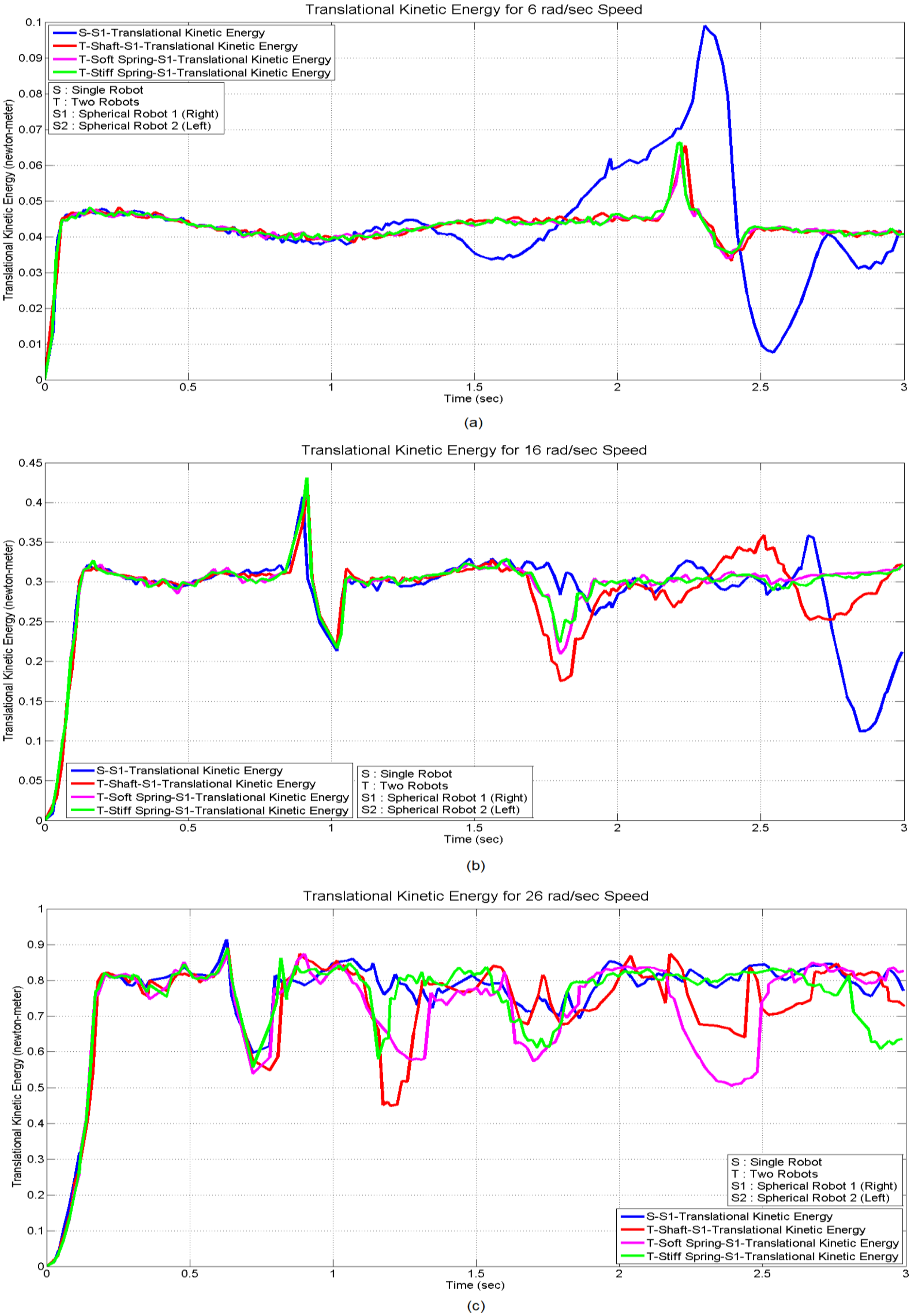


Figure 68: Translational kinetic energy for first random shaped road (a) for 6 rad/sec (b) for 16 rad/sec (c) for 26 rad/sec

4.4. Second Random Shaped Road Analyses Data

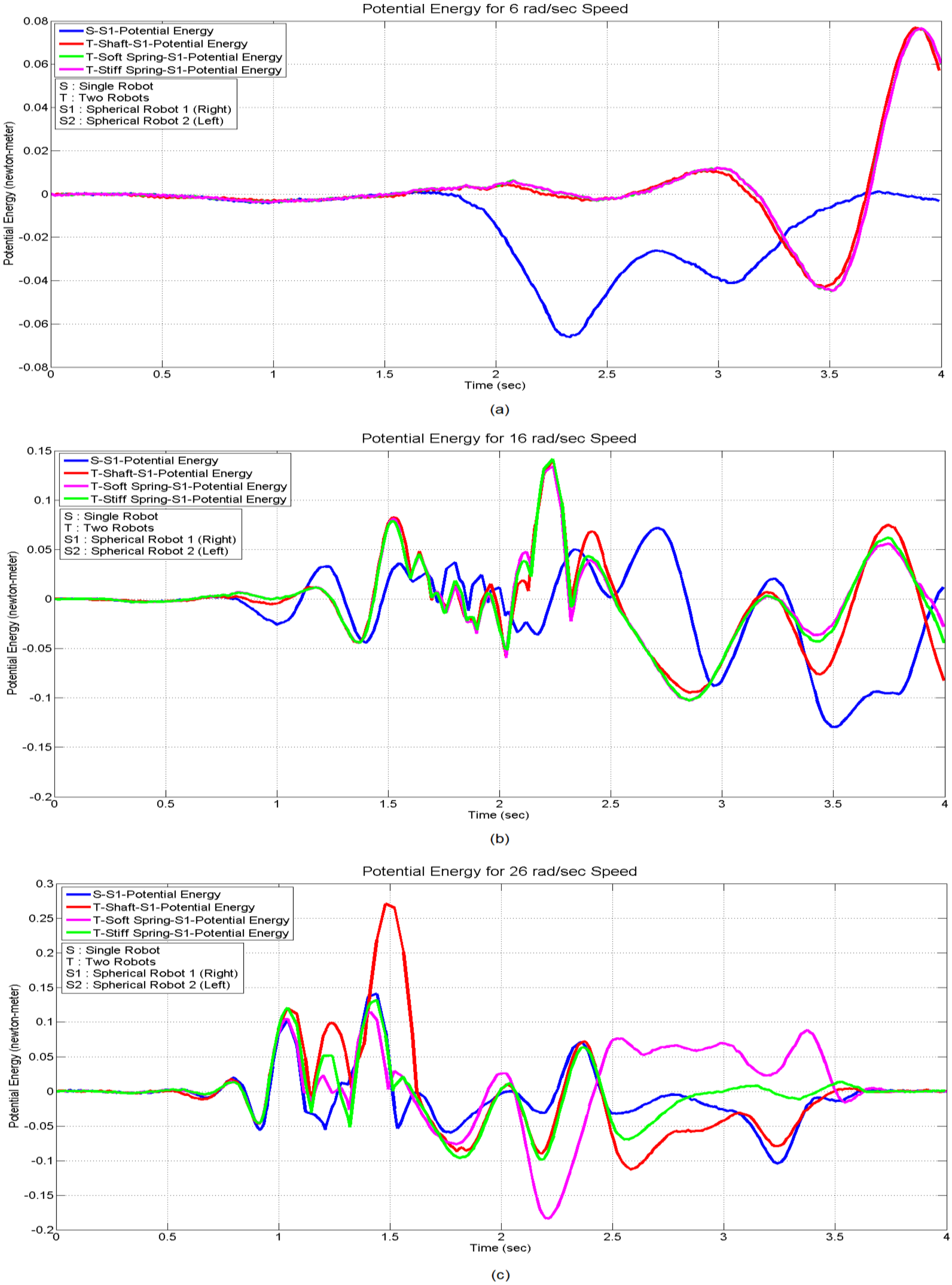


Figure 69: Potential energy for second random shaped road (a) for 6 rad/sec (b) for 16 rad/sec (c) for 26 rad/sec

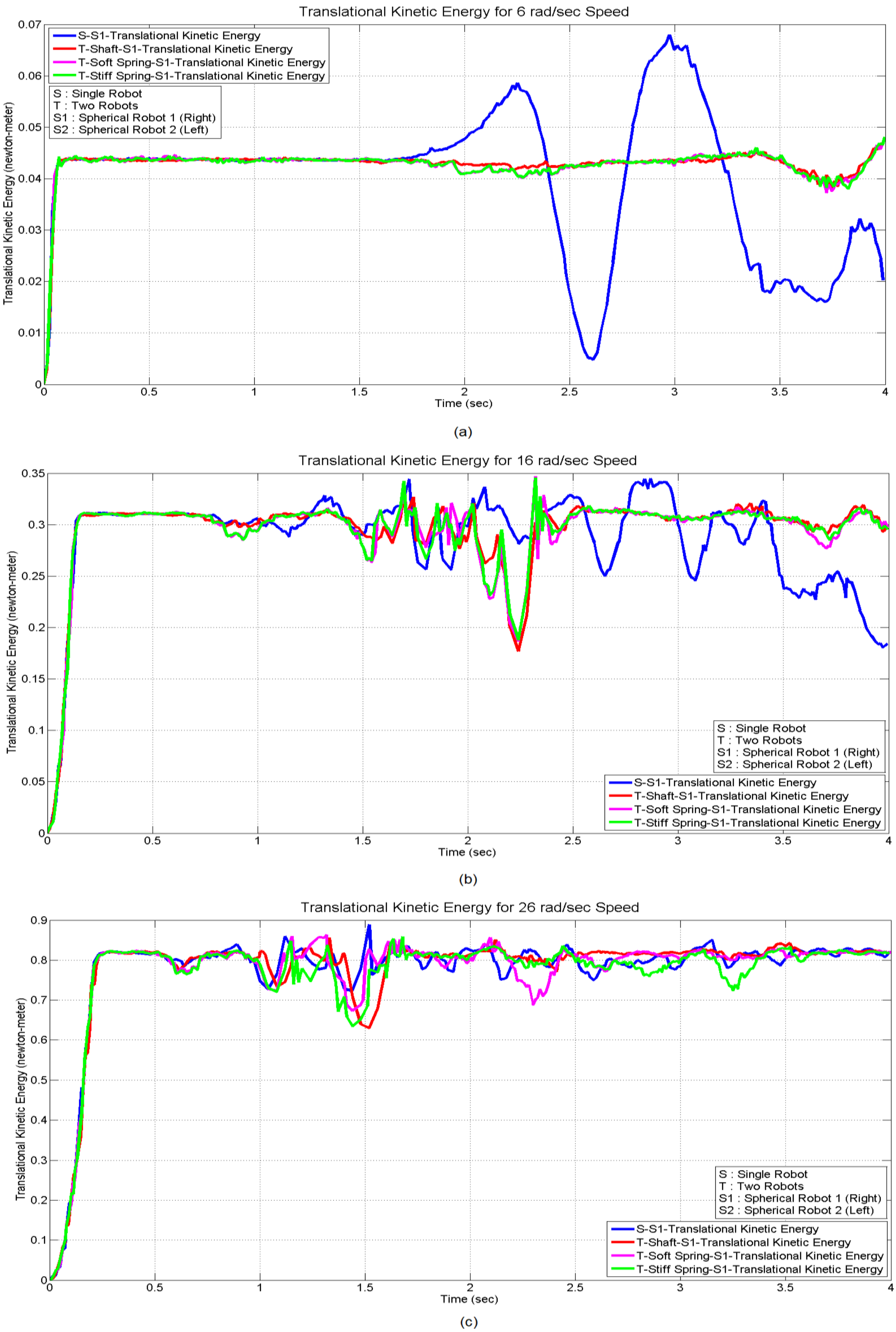


Figure 70: Translational kinetic energy for second random shaped road (a) for 6 rad/sec (b) for 16 rad/sec (c) for 26 rad/sec

When we look at translational kinetic energy curves for speed of 6,16,26 rad/sec on flat asphalt and icy roads for four simulation modeling, we will see the same curves. Just we can say, on the icy road, the kinetic energy of robots are reaching the maximum a little late because of skidding.

On the dual flat road, while there was no significant change in the potential energy and translational kinetic energy curves at speeds of 6 and 16 rad/sec, a significant change in shaft connection at 26 rad/sec was observed. The reason for this result is, while the second spherical robot that at 26 rad/sec from the asphalt road moving towards the icy road, affected the first robot that on the icy road. There was no significant change in torsional spring connections and the single robot simulation models.

When we examine the analyses on both randomly shaped roads, it is seen that the single spherical robot makes unstable movements due to the obstacles it encounters (Moazami et al., 2019b). Compared to this, other models have progressed in a more balanced manner. In Figure 69 - (c), shaft connection modeling in some obstacles like in the 1.4th second and torsional soft spring coupled modeling in some obstacles like in the 2.2th second in Figure 67 - (c) made leaps. In torsional stiff spring connections, such movements were observed at a minimum level and continued to progress by adapting to surface profiles.

As can be seen in Figure 65, the effect of robots on each other is minimized thanks to the spring connections between different surfaces. In addition, by looking at the analysis made on randomly shaped roads, it was decided to prefer this modeling in our design due to the comprehensive mobility of torsional stiff spring coupled modeling.

There is a crucial advantage of using torsional springs as a connecting part. This advantage is that the torsional springs can apply extra momentum. For instance, if one of the two spherical robots skidding on a muddy surface, the movement will restrict. When the other robot continuing to move, the movement restriction will be minimized by applying an extra moment as a result of the potential energy increase in the torsional spring.

When we look at the experimental results, we realize similarities with the analysis results. Particularly, on both randomly shaped roads, while the single spherical robot is making unstable movements, it is observed that two identical coupled spherical robot designs have more balanced motion.

Such as analysis results, the effect of robots on each other is minimized thanks to the spring connections. The most balanced movement was observed with torsional stiff spring coupled modeling.

Figure 71: Qr code of google drive for videos of analyses and experiments

5. CONCLUSION AND RECOMMENDATIONS

Spherical robots have been used in many fields from past to present such as Jones (Jones, 2001), Ylikorpi (Ylikorpi et al., 2005) which are designed for use in space studies, Mine Kafon (Hassani, 2008) which can be used to clear mined areas, they are spherical robots designs that run with wind energy, the underwater spherical robot designed (MIT, 2011) to detect leaks in nuclear reactor cooling systems, the spherical robot that used in agriculture (Hernández et al., 2013), the Rotundus Groundbot (Rotundus, 2010) security robot designed for surveillance, and the Surveillance Robot that can easily navigate on snowy and muddy surfaces (Knight, 2005). Their use in future studies is inevitable, too. We can give a few examples for this, one of them is the spherical robot that Japan is going to send in 2022 to explore the Moon (Space,), the other one is the DAEDALUS project.

(‘’*The DAEDALUS mission design concept aims at exploring and characterizing the entrance of lunar lava tubes within a compact, tightly integrated spherical robotic device, with a complementary payload set and autonomous capabilities.’’)* (Rossi et al., 2021).

The feasibility of our design of two identical coupled spherical robots has been proven by dynamic analyses and experiments. This design is expected to be used both in omnidirectional mobile robots and in tasks such as imaging, transport.

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APPENDICES

APPENDIX 1

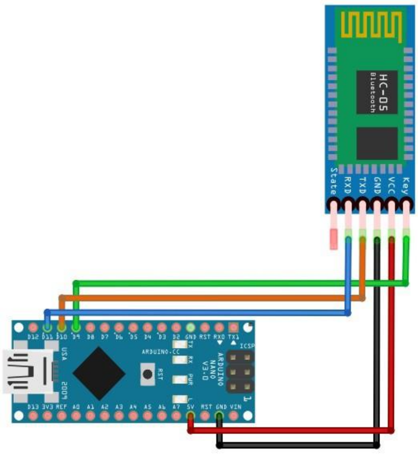

Figure 72: Required circuit diagram for setting as a master or slave mode of hc-05 bluetooth module

```
#include <SoftwareSerial.h>
SoftwareSerial mySerial(10, 11); // RX, TX

void setup() {
  Serial.begin(38400);
  pinMode(9,OUTPUT);
  digitalWrite(9,HIGH);
  Serial.println("Enter AT commands:");
  mySerial.begin(38400);
}

void loop()
{
  if (mySerial.available())
    Serial.write(mySerial.read());
  if (Serial.available())
    mySerial.write(Serial.read());
}
```

Figure 73: Required codes for setting as a master or slave mode of hc-05 bluetooth module

APPENDIX 2

```
*******************************************
AT CODES FOR SLAVE 1
*******************************************
AT+NAME=SLAVE
AT+ROLE=0
AT+CMODE=1
AT+UART=38400,0,0
AT+ADDR=(ADRESS)
*******************************************
AT CODES FOR MASTER 1
*******************************************
AT+NAME=MASTER
AT+ROLE=1
AT+CMODE=0
AT+UART=38400,0,0
AT+BIND=18,E4,400006 (ADRESS OF SLAVE 1)
*******************************************
*******************************************
AT CODES FOR SLAVE 2
*******************************************
AT+NAME=SLAVE
AT+ROLE=0
AT+CMODE=1
AT+UART=38400,0,0
AT+ADDR=(ADRESS)
*******************************************
AT CODES FOR MASTER 2
*******************************************
AT+NAME=MASTER
AT+ROLE=1
AT+CMODE=0
AT+UART=38400,0,0
AT+BIND=0019,07,001DDB (ADRESS OF SLAVE 2)
*******************************************
```

Figure 74: At codes for setting as a master or slave mode of hc-05 bluetooth module

APPENDIX 3

```
#define enA 10
#define in1 9
#define in2 8
#define enB 5
#define in3 7
#define in4 6
int xAxis, yAxis;
unsigned int  x = 0;
unsigned int  y = 0;
int motorSpeedA = 0;
int motorSpeedB = 0;
void setup() {
  pinMode(enA, OUTPUT);
  pinMode(enB, OUTPUT);
  pinMode(in1, OUTPUT);
  pinMode(in2, OUTPUT);
  pinMode(in3, OUTPUT);
  pinMode(in4, OUTPUT);
  Serial.begin(38400); // Default communication rate of the Bluetooth module
}
void loop() {
  // Default value - no movement when the Joystick stays in the center
  x = 510 / 4;
  y = 510 / 4;
  // Read the incoming data from the Joystick, or the master Bluetooth device
  while (Serial.available() >= 2) {
    x = Serial.read();
    delay(10);
    y = Serial.read();
  }
  delay(10);
  // Convert back the 0 - 255 range to 0 - 1023, suitable for motor control code below
  xAxis = x*4;
  yAxis = y*4;
  // Y-axis used for forward and backward control
  if (yAxis < 470) {
    // Set Motor A backward
    digitalWrite(in1, HIGH);
    digitalWrite(in2, LOW);
    // Set Motor B backward
    digitalWrite(in3, HIGH);
    digitalWrite(in4, LOW);
    // Convert the declining Y-axis readings for going backward from 470 to 0 into 0 to 255 value for the PWM signal for increasing the motor speed
    motorSpeedA = map(yAxis, 470, 0, 0, 255);
    motorSpeedB = map(yAxis, 470, 0, 0, 255);
  }
```

Figure 75: Arduino codes for spherical robots (slave) (Howtomechatronics, 2017b)

APPENDIX 4

```
  else if (yAxis > 550) {
    // Set Motor A forward
    digitalWrite(in1, LOW);
    digitalWrite(in2, HIGH);
    // Set Motor B forward
    digitalWrite(in3, LOW);
    digitalWrite(in4, HIGH);
    // Convert the increasing Y-axis readings for going forward from 550 to 1023 into 0 to 255 value for the PWM signal for increasing the motor speed
    motorSpeedA = map(yAxis, 550, 1023, 0, 255);
    motorSpeedB = map(yAxis, 550, 1023, 0, 255);
  }
  // If joystick stays in middle the motors are not moving
  else {
    motorSpeedA = 0;
    motorSpeedB = 0;
  }
  // X-axis used for left and right control
  if (xAxis < 470) {
    // Convert the declining X-axis readings from 470 to 0 into increasing 0 to 255 value
    int xMapped = map(xAxis, 470, 0, 0, 255);
    // Move to left - decrease left motor speed, increase right motor speed
    motorSpeedA = motorSpeedA - xMapped;
    motorSpeedB = motorSpeedB + xMapped;
    // Confine the range from 0 to 255
    if (motorSpeedA < 0) {
      motorSpeedA = 0;
    }
    if (motorSpeedB > 255) {
      motorSpeedB = 255;
    }
  }
  if (xAxis > 550) {
    // Convert the increasing X-axis readings from 550 to 1023 into 0 to 255 value
    int xMapped = map(xAxis, 550, 1023, 0, 255);
    // Move right - decrease right motor speed, increase left motor speed
    motorSpeedA = motorSpeedA + xMapped;
    motorSpeedB = motorSpeedB - xMapped;
    // Confine the range from 0 to 255
    if (motorSpeedA > 255) {
      motorSpeedA = 255;
    }
    if (motorSpeedB < 0) {
      motorSpeedB = 0;
    }
  }
  // Prevent buzzing at low speeds (Adjust according to your motors. My motors couldn't start moving if PWM value was below value of 70)
  if (motorSpeedA < 70) {
    motorSpeedA = 0;
  }
  if (motorSpeedB < 70) {
    motorSpeedB = 0;
  }
  analogWrite(enA, motorSpeedA); // Send PWM signal to motor A
  analogWrite(enB, motorSpeedB); // Send PWM signal to motor B
}
```

Figure 76: Arduino codes for spherical robots (continued) (slave) (Howtomechatronics, 2017b)

APPENDIX 5

```
int xAxis, yAxis;
void setup() {
  Serial.begin(38400); // Default communication rate of the Bluetooth module
}
void loop() {
  xAxis = analogRead(A0); // Read Joysticks X-axis
  yAxis = analogRead(A1); // Read Joysticks Y-axis

  // Send the values via the serial port to the slave HC-05 Bluetooth device
  Serial.write(xAxis/4); // Dividing by 4 for converting from 0 - 1023 to 0 - 256, (1 byte) range
  Serial.write(yAxis/4);
  delay(20);
}
```

Figure 77: Arduino codes for joystick (master) (Howtomechatronics, 2017b)

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SCIENTIFIC ETHICS STATEMENT

I hereby declare that I composed all the information in my master's thesis entitled "Dynamic Modeling of Two Identical Coupled Spherical Robots" within the framework of ethical behavior and academic rules and that due references were provided and for all kinds of statements and information that do not belong to me in this study in accordance with the guide for writing the thesis. I declare that I accept all kinds of legal consequences when the opposite of what I have stated is revealed.

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18/08/2021

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