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Trajectory Scenario Control for the Remotely Operated Mobile Robot LIPI Platform Based on Energy Consumption Analysis

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Abstract

To accomplish a given mission the remotely operated Mobile Robot LIPI, which is called MoroLIPI, has to choose the best trajectory among others. A supervisory controller is designed to provide trajectory scenario control considering characteristics of the trajectory including distance, obstacles, inclining ramps, and the suitable robot movement modes. This work provides analysis of energy consumption on the mobile robot platform based on experimental results and proposes a trajectory scenario control which minimizes energy consumption. The robot has a combination of locomotion systems between 4-wheels skid steering system and tracked locomotion system. In this experiment electric current and voltage of the left and right sides DC motors as well as angular velocity of the right and left sides of locomotion systems were measured. The experiment result is used as a database of energy consumption for each identified movement mode. A trajectory scenario control algorithm is proposed based on estimated energy consumption required to complete a mission along a certain trajectory. From simulation it is concluded that the algorithm selects a trajectory which requires the least energy consumption and not the shortest trajectory.

Keywords: trajectory scenario control, mobile robot, MoroLIPI, energy consumption.

Introduction

Research activities on wheeled mobile robots, tracked mobile robots, and legged mobile robots have significant growth [1]. Many applications are offered by mobile robots those are surveillance, security, exploration, logistic, inspection, and so on [2] [3] [4]. Different applications require the mobile robots to operate in different environments [5]. For instance in exploration, they are used for search and rescue outdoor, such as a mars robotic explorer. In security application, they are used in police operation such as explosive ordnance disposal robots (EOD Robots). Such a robot must have ability to operate both indoor and outdoor.

In the research centre for electrical power and mechatronics (P2 Telimek) – Indonesian Institute of Sciences (LIPI), design and development of a mobile robot has been done. In 2009, a mobile robot prototype named Mobile Robot LIPI V.1 (known as MoroLIPI) was finished. It has ability to climb stairs with slope 16°, and can pass through an obstacle having height of 10 cm. The dimension of this robot is 190 x 190 x 190 cm, and 190 kg in weight. It has a combined drive train mechanism between 4 wheels mechanism, 2 tracks mechanism and 4 flippers mechanism to allow the robot to be operated in all terrain conditions [6].

One key aspect of vehicle autonomy is power consumption which has become particularly relevant in applications with critically limited power sources [7]. Most of mobile robots including the MoroLIPI are equipped with batteries as energy source. As the consequences, they have limited operation time depending on battery capacity. Thus power efficiency is very important to have a long time operation robot [8].

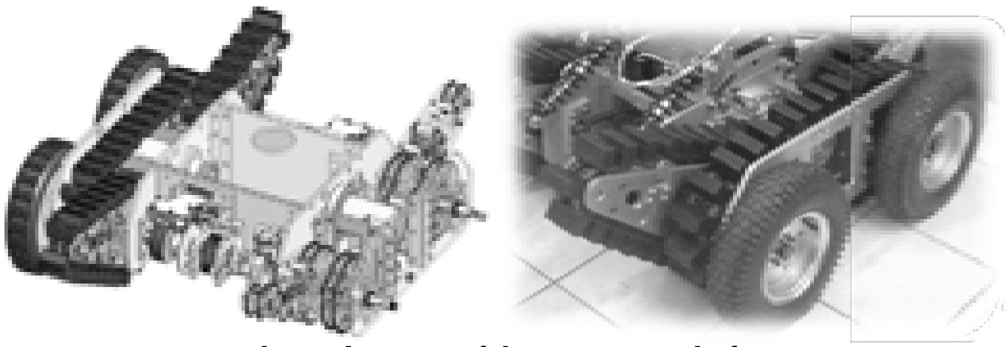
Some researchers have begun to analyze power consumption and efficiency related to application of mobile robots. A tracked locomotion system offers a large contact area with the ground which provides better traction than wheels on natural terrains [9] [10]. However, power consumption is much higher than wheeled robots because of friction and slippage. In this kind of vehicle, power dissipation due to track-soil interactions is considerably larger than that of motor resistances [10]. Power consumption has also been studied for alternative locomotion mechanisms, such as wheeled vehicles with redundant drives [11], limbed robots [12], snake-like robots [13], or tracked mobile robot [10].

Meanwhile some researchers have begun to develop navigation ability to support vehicle autonomy applications. A navigation system will give information about trajectory scenario to a mobile robot supervisory controller and determine the optimum trajectory based on appropriate information [14]. Some methods have been provided to get the optimum trajectory in autonomous mobile robot applications. Most of them use information about the distance of the path, and the number of obstacles, such as the research conducted by Hachour [15] which uses the grid-map to specify the path planning in static environments. Giham et al. [16], Ismail et. al. [17] use genetic algorithm to determine optimal path planning based on the shortest path and capability of a mobile robot to avoid a number of obstacles.

In this paper, we analyze power consumption of MoroLIPI platform in some movement modes based on experiment results. By using the energy consumption database obtained through the experiment, we propose a simple algorithm to control the MoroLIPI select a trajectory which requires the least energy consumption among other possible trajectories.

Mobile Robot MoroLIPI Platform System Overview

The mechanical system of MoroLIPI platform uses a combination system which is composed by two tracked locomotion systems, 4-static flippers and a 4-wheel skid steering locomotion system. These locomotion systems are actuated by two Direct Current (DC) motors which use differential drive system type [18]. Gear and chain transmission systems are used to transmit mechanical power from DC motor to locomotion system. The locomotion system model of this robot can be approximated by a combination of tracked system model and skid steering wheeled locomotion system model. The mechanical system of MoroLIPI platform is shown in figure 1.



Mechanical system of the MoroLIPI platform

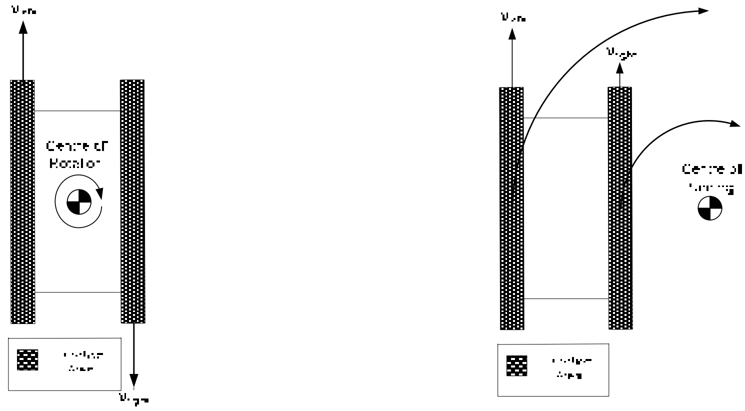
(b) Gear transmission system (c) Belt transmission system

Figure 1: Mechanical system of MoroLIPI platform [18]

Tracked locomotion system model

Three locomotion systems have been proposed for tracked vehicles by previous researchers which include articulated steering, curved track steering, and skid steering [19] [20] [10]. The most widely used system is the skid steering system because it is simple from the mechanical stand point [19]. The model of this system can be seen in figure 2. Controlling the direction can be done by controlling the relative velocity between left track and right track. This is widely known as differential drive system. When both of the tracks have the same velocity, the robot will move forward and backward in straight direction. If there is velocity difference, the robot will turn around a Centre of Turning. The faster track will around in external side and the slower one will around in internal side. Both tracks can be regarded as external in straight line motion or when rotating around the vehicle's center [19].

More detailed discussion about centre of turning of tracked robots can be found in [21].



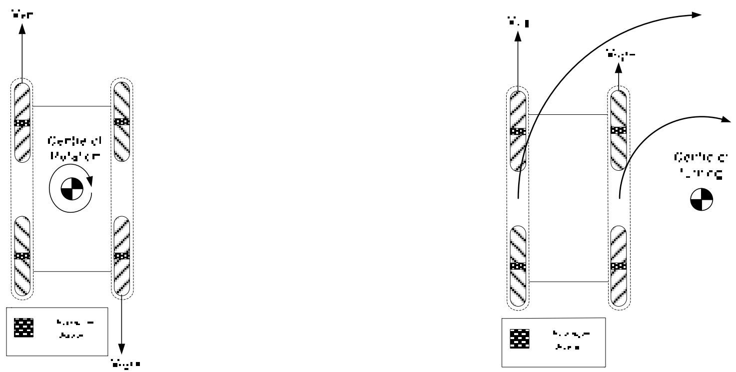
(a) Rotating movement Turning movement

Figure 2: Skid steering tracked locomotion system model

Turning in a skid-steering vehicle is the cause of high losses of energy. Because when the tracks turn around the Centre of Turning or Rotating, it will cause friction between the tracks and the runway. The larger the contact area between the track and the runway will lead to greater energy losses that occur due to friction.

4-wheel skid steering locomotion system model

The mechanism of skid steering wheeled locomotion system in general is similar with the skid steering tracked locomotion system. The model of this locomotion system can be seen in figure 3.

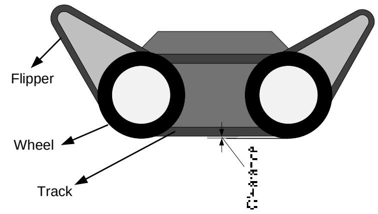


(a) Rotating movement (b) Turning movement

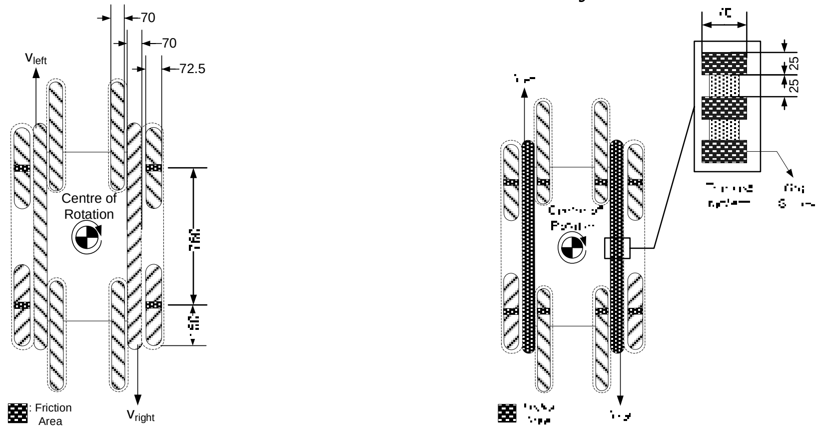
Figure 3: Skid steering wheeled locomotion system model

The difference is that the contact area between wheeled mobile robot and the road is less than the contact area between tracked mobile robot and the road. So that, the losses energy caused by the friction when the mobile robot turning or rotating is smaller. However it causes the power of their grip in this robot is smaller than in the tracked robot. As a result, this locomotion system isn't so good if it is used in rough terrain like as on the sand, soil, rocky road, and so forth.

Approximation model for a combined locomotion system (MoroLIPI locomotion)
Approximation model of the locomotion system of MoroLIPI can be seen in the figure 4.



Side view of MoroLIPI locomotion system



(b) friction area on flat terrain (c) friction area on rough terrain

Figure 4: MOROLIPI approximation locomotion system model

The locomotion system of MoroLIPI platform combines the three systems in one mobile robot including 4-wheel skid steering system, 2-tracked system, and 4-static flipper. The wheeled and tracked systems are used to overcome all terrain conditions, and the 4-static flippers are used to climb up stair and to pass through an obstacle.

Experimental Method

Figure 5 shows the block diagram of experiment process to obtain data for energy consumption analysis. The measured variables are velocity of right and left side wheels and tracks, real time electric current and voltage supply of right and left DC motors. To measure the data, current and voltage sensors are installed in each DC motor on right and left sides. Two optical rotary encoders are used for measuring the velocity data which are installed on left and right sides locomotion mechanism. The data from each sensor is transmitted to computer using a microcontroller as the data logger. The serial communication is used to transmit data from the microcontroller to the host computer in a real time manner.

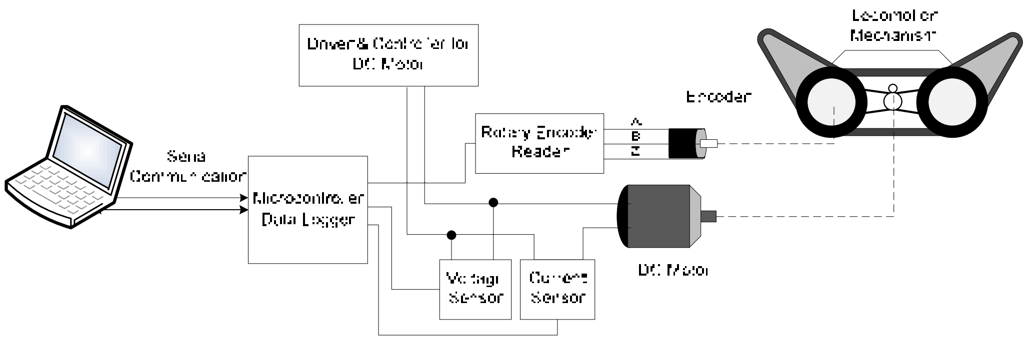


Figure 5: Block diagram of the experiment process

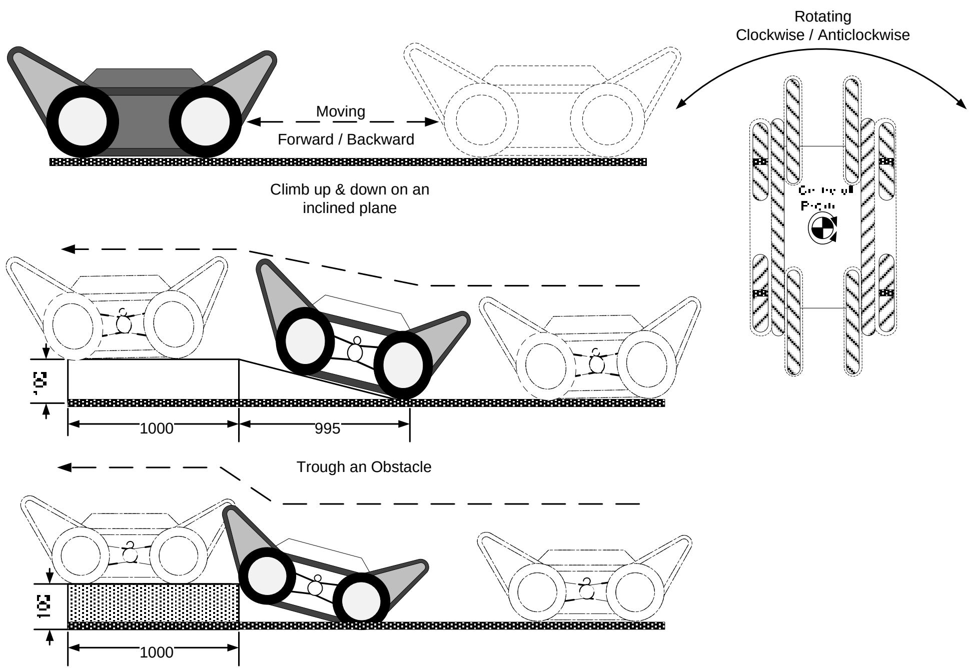


Figure 6: Illustration of various operating conditions during experiment.

In this experiment, the operating conditions are illustrated in figure 6 and listed in table 1. During experiment, electric current and voltage of each DC motor as well as angular velocity of both left and right side locomotion systems were measured with sampling time of 0.1 sec.

Table 1: Operating Conditions of Experiment.

Operating Condition	Description	Remarks
1	Moving straight forward/backward	On concrete road
2	Slope Climbing	Poly wood, inclination 5.7°
3	Passing through an obstacle	Obstacle height 10 cm.
4	Rotating	On concrete road

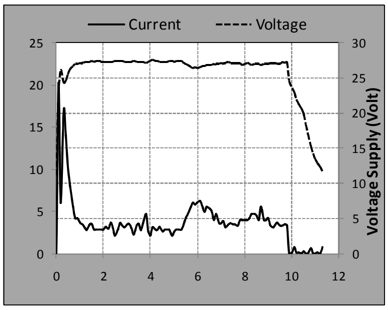
Results and Discussion

Using the measured angular velocity ω the linear speed $\boldsymbol{v}$ can be calculated using the following equation.

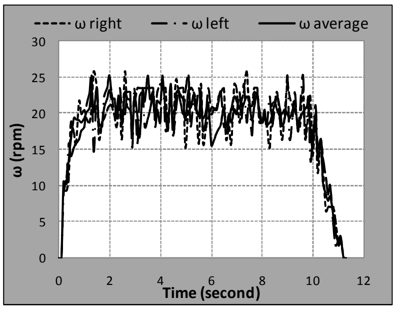
$$\boldsymbol{v} = \boldsymbol{\omega r} \quad (1)$$

where r denotes the effective radius of the wheel. Electrical power P consumed by the robot can be calculated using the measured voltage V and current I as follows.

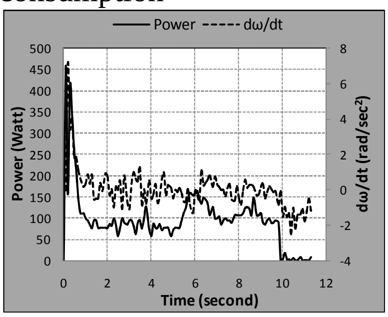
$$\boldsymbol{P} = \boldsymbol{VI} \quad (2)$$



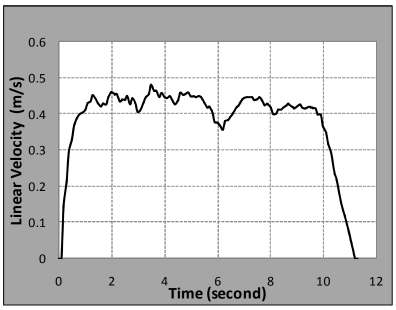
(a) Voltage supply and current consumption



(b) angular velocity of the drive trains



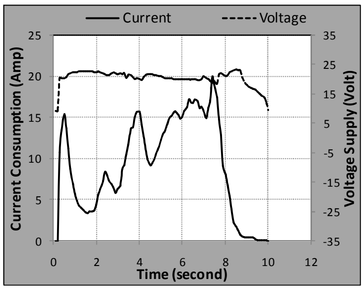
(c) power consumption and angular acceleration of the drive trains



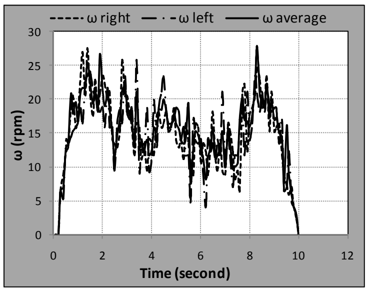
(d) linear velocity of MoroLIPI

Figure 7: Experiment results when the MoroLIPI moves forward on the flat plane

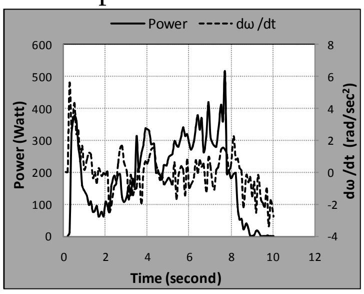
Figure 7 shows experiment results under operating condition 1. In figure 7(a), the broken line denotes voltage and the solid line denotes electric current. Figure 7(b) plots angular velocity of right side wheel (broken line), left side wheel (dotted line) and average value (solid line). Figure 7(c) exhibits electric power (solid line) and angular acceleration (broken line). Figure 7(d) shows linear velocity of the robot. Some important information can be derived. When the power is switched on the robot experiences acceleration during the first 1 sec, then it moves at relatively constant speed of 20.9 rpm until the power is switched off at time 9.9 sec. After the power is switched off it needs 1.3 sec for the robot to stop after experiencing deceleration. During the power is on, the voltage keeps relatively constant at 22.6 Volt while the current first forms spike with high peak value and then remains relatively constant at 4.4 Ampere. During acceleration in the first 1 sec, the robot consumes energy 234 Joule with the maximum instantaneous power of 410 Watt. During the constant speed movement the robot consumes power 98.5 Watt. Total friction torque at the constant speed movement is 45.1 Nm.



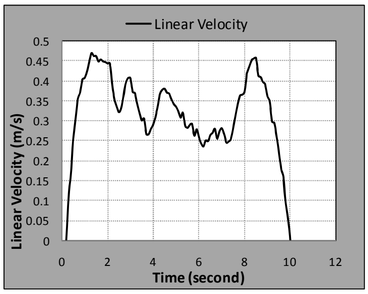
(a) Voltage supply and current consumption



(b) angular velocity of the drive trains



(c) power consumption and angular acceleration of the drive trains

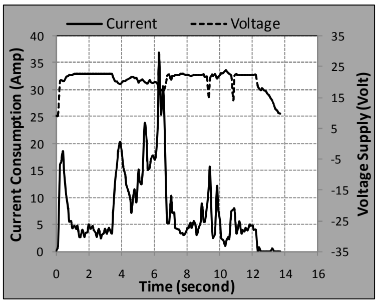


(d) linear velocity of MoroLIPI

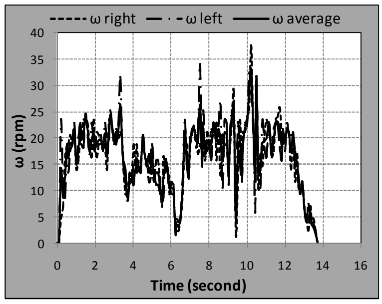
Figure 8: Experiment results when the MoroLIPI moves climbing up the inclined plane

Figure 8 shows experiment results under operating condition 2. Notation in figure 8 is the same as that in figure 7. When the power is switched on the robot experiences acceleration during the first 1 sec, then it moves at relatively constant speed of 21.7 rpm until the robot reaches the ramp. During this period the voltage keeps relatively constant at 21.5 Volt while the current first forms spike with high peak value and then remains relatively constant at 3.6 Ampere. During acceleration in the first 1 sec, the robot consumes energy 222 Joule with the maximum instantaneous power of 377 Watt. During the constant speed movement the robot consumes power 80.5 Watt. Total friction torque at the constant speed movement is 35.5 Nm.

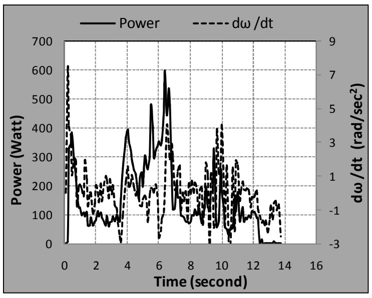
The robot then experienced climbing transition condition where the front wheel is on the ramp but the rear wheel is still on the ground. During the climbing transition the current rises and the speed decreases. The robot completed the climbing transition mode in 3.3 sec by consuming energy 750 Joule. Then the robot moved climbing on the poly wood ramp using its front and rear wheels at the average speed of 12.4 rpm by consuming average power of 336 Watt.



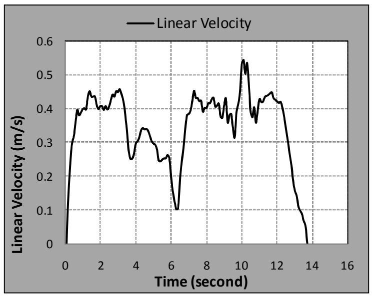
(a) Voltage supply and current consumption



(b) angular velocity of the drive trains



(c) power consumption and angular acceleration of the drive trains

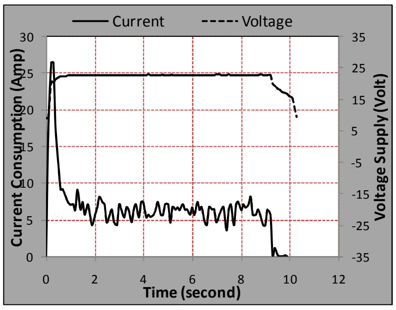


(d) linear velocity of MoroLIPI

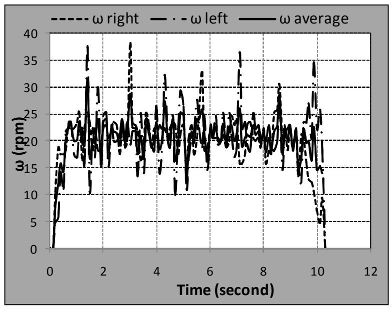
Figure 9: Experiment results when the MoroLIPI passes through the obstacle

Figure 9 shows experiment results of the operating condition 3. Notation in figure 9 is the same as that in figure 8.When the power is switched on the robot experiences acceleration during the first 1 sec, it then moves at relatively constant speed of 20.2 rpm until the robot reaches the obstacle. During this period the voltage keeps relatively constant at 22.6 Volt while the current first forms spike with high peak value and then remains relatively constant at 3.7 Ampere. During acceleration in the first 1 sec, it consumes energy 222 Joule with the maximum instantaneous power of 381 Watt. During the constant speed movement it consumes power 83.1 Watt. Total friction torque at the constant speed movement is 39.4 Nm. During the robot's endeavor to overtake the obstacle the current rises and the speed decreases. There is a moment when the robot is almost stationary with the minimum speed of 2 rpm. It took over the obstacle in 3.4 sec by consuming energy 1100 Joule. After having taken over the obstacle it moves on the wood pallet at the average speed of 19.7 rpm by consuming average power of 105.6 Watt.

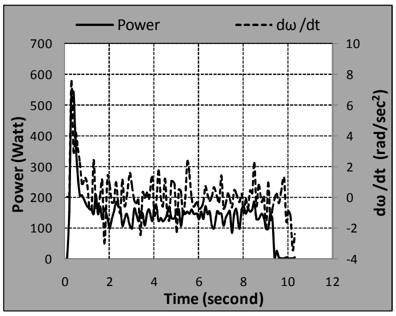
Figure 10 shows experiment results of the operating condition 4. Notation in figure 10 is the same as that in figure 9. When the power is switched on the robot experiences acceleration during the first 1 sec, then it moves at relatively constant speed of 20.7 rpm until the power is switched off. During the power is on, the voltage keeps relatively constant at 22.7 Volt while the current first forms spike with high peak value and then remains relatively constant at 6.2 Ampere. During acceleration in the first 1 sec, the robot consumes energy 299 Joule with the maximum instantaneous power of 545 Watt. During the constant speed movement the robot consumes power 141.5 Watt. Total friction torque at the constant speed movement is 65.2 Nm.



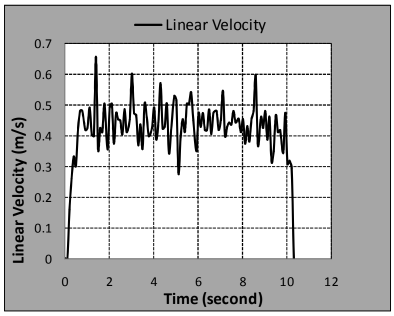
(a) Voltage supply and current consumption



(b) angular velocity of the drive trains



(c) power consumption and angular acceleration of the drive trains



(d) linear velocity of MoroLIPI

Figure 10: Experiment results when the MoroLIPI rotates

By observation of the above experiment results it is obvious that any operating mode in the experiment can be constructed by combination of certain motion category namely: Straight Start (SS), Rotate Start (RS), Straight Moving (SM), Rotate Moving (RM), Slope Climbing Transition (SCT), Slope Climbing Moving (SCM), and Passing Through Obstacle (PTO). Every movement category has each power/energy consumption characteristics as shown in table 2.

Table 2: Database of energy consumption according to movement category based on experiment results.

Movement Category	Power (Watt)	Energy (Joule)	Remarks
Straight Starting (SS)	-	226	Completed in 1 sec
Rotate Starting (RS)	-	299	Completed in 1 sec
Straight Moving (SM)	87,4	-	Speed 21 rpm, friction 45 Nm.
Rotate Moving (RM)	141,5	-	Speed 21 rpm, friction 65 Nm.
Slope Climbing Transition (SCT)	-	750	Completed in 3,3 sec
Slope Climbing Moving (SCM)	336	-	Speed 12 rpm.
Passing Through Obstacle (PTO)	-	1100	Completed in 3,4 sec.

Based on the database in table 2, energy consumption of MoroLIPI in a variety of operation conditions can be estimated by using the following formulae.

$$\boldsymbol{E_{total}} = (\boldsymbol{n})\boldsymbol{SS} + (\boldsymbol{s})\boldsymbol{SM} + \boldsymbol{n}(\boldsymbol{RS}) + (\boldsymbol{\theta})(\boldsymbol{RM}) + \boldsymbol{n}(\boldsymbol{SCT}) + (\boldsymbol{s})(\boldsymbol{SCM}) + (\boldsymbol{n})(\boldsymbol{PTO}) \quad (3)$$

n is total number of the corresponding movement mode, and *s* is total moving distance of the corresponding movement mode. θ and *E* denote total rotating angle of the rotate moving mode and energy consumption (Joule), respectively.

On the other hand, operating time *t* can be calculated using the following equation.

$$\boldsymbol{t_{total}} = \boldsymbol{n}(\boldsymbol{tSS}) + \boldsymbol{f}(\boldsymbol{s})(\boldsymbol{vSM}) + \boldsymbol{n}(\boldsymbol{tRS}) + \boldsymbol{f}(\boldsymbol{\theta})(\boldsymbol{\omega RM}) + (\boldsymbol{n})(\boldsymbol{tSCT}) + \boldsymbol{f}(\boldsymbol{s})(\boldsymbol{tSCM}) + (\boldsymbol{n})(\boldsymbol{PTO}) \quad (4)$$

To minimize total energy consumption and operating time of MoroLIPI in completing a given mission, the following things need to be considered: (1) the number of straight starting of mobile robot, (2) the number of rotating starting of mobile robot, (3) the length of the straight path that must be passed, (4) total rotation angle to be done, (5) the number of climbing transition, (6) the length of the inclined trajectory, and (7) the number of obstacle that must be passed.

By considering the magnitude of each parameter, based on the database in table 2, a simple algorithm as shown in the figure 11 has been made to obtain the most optimal trajectory planning.

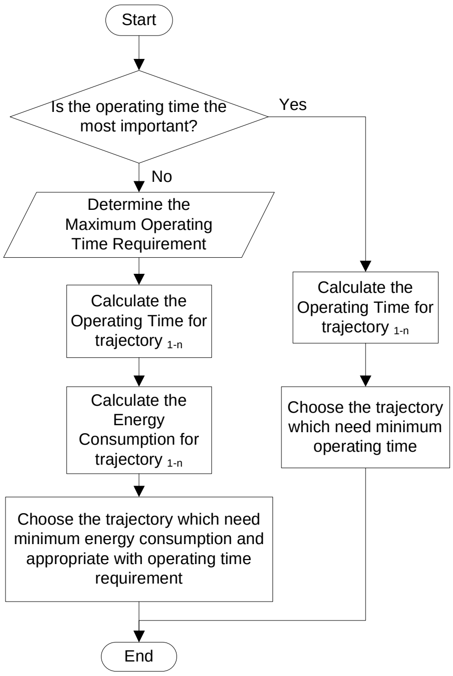


Figure 11: The proposed simple algorithm to determine optimal trajectory planning.

To prove the proposed algorithm, a simulation of four trajectory scenarios with different combinations of terrain conditions shown in figure 12 has been conducted.

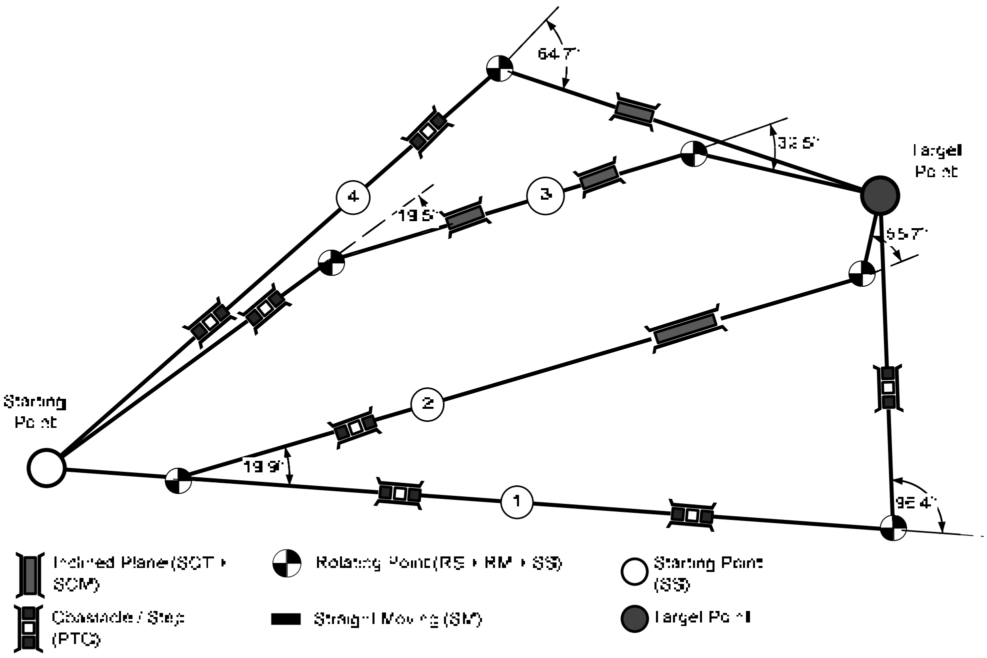


Figure 12: Simulation of four trajectories scenario planning.

Given possible trajectories shown in figure 12, firstly the supervisor controller analyzes number/length of movement modes of each movement category. Table 3 shows its analysis results.

Table 3: Combination of movement types for each trajectory planning.

Trajectory Planning	Operating Type						
	SS(n)	SM(m)	RS(n)	RM(θ^o)	SCT(n)	SCM(m)	PTO(n)
Trajectory 1	2	32	1	96.4^o	-	-	3
Trajectory 2	3	24	2	75.6^o	1	1.25	1
Trajectory 3	3	23	2	52^o	2	0.5	1
Trajectory 4	2	26.5	1	64.7^o	1	0.25	2

Secondly, the supervisory controller calculate energy consumption using equation 3 based on database in table 2 and analysis results in table 3. The calculated energy consumption of each trajectory is shown in table 4.

Table 4: Estimated energy consumption of each trajectory

Operating Description	Energy Consumption (Joule)							Total Energy Consumption
	SS	SM	RS	RM	SCT	SCM	PTO	
Trajectory 1	452	8475	299	554	-	-	3300	13080
Trajectory 2	678	6356	598	432	750	420	1100	10334
Trajectory 3	678	6092	598	298	1500	168	1100	10434
Trajectory 4	452	7019	299	370	750	84	2200	11174

Thirdly, the supervisory controller calculate operation time using equation 4 based on database in table 2 and analysis results in table 3. The calculated operation time of each trajectory is shown in table 5.

Table 5: Operation time in each path planning

Operating Description	Operation time (second)							Total Operation time
	SS	SM	RS	RM	SCT	SCM	PTO	
Trajectory 1	2	96.97	1	0.76	-	-	10.2	110.93
Trajectory 2	3	72.73	2	0.60	3.3	6.94	3.4	91.97
Trajectory 3	3	69.70	2	0.41	6.6	2.78	3.4	87.89
Trajectory 4	2	80.30	1	0.51	3.3	1.39	6.8	95.29

Finally, based on the estimated energy consumption and operation time of each trajectory, the supervisory controller selects a trajectory as the optimum trajectory according to a desired performance index. The trajectory which provides minimum energy consumption is trajectory 2 while the trajectory which provides minimum operation time is trajectory 3.

Conclusion

Energy consumption database of the MoroLIPI platform has been obtained through experiment which categorized motion into starting mode, slope climbing transition mode, obstacle overtaking mode, straight moving mode, rotating mode, and slope climbing mode. The robot platform completes straight starting mode in 1 sec by consuming energy 226 Joule and completes rotate starting mode in 1 sec by consuming energy 299 Joule. When climbing a slope of angle 5,7˚ it can complete slope climbing transition mode in 3,3 sec by consuming 750 Joule of energy. When going through an obstacle 10 cm in height it can complete overtaking the obstacle in 3,4 sec by consuming 1100 Joule. The robot platform consumes power 87,4 Watt for straight moving and 141,5 Watt for rotate moving on concrete road, thus rotate moving consumes 62% more power than straight moving. Moreover, when the robot moves climbing an inclined plywood with angle of 5,7˚ it consumes power 336 Watt.

Based on the energy consumption database, a trajectory scenario control algorithm has been made to estimate energy consumption and operating time required by possible trajectories to accomplish a given mission. A simulation was conducted by giving 4 alternative trajectories and it is obtained that the control algorithm recommends trajectory 2 which minimizes energy consumption. However, if time becomes the highest priority it recommends trajectory 3 which minimizes time consumption.

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