# Rule-Based Control Application on Multimode Cricket Bowling Machine

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**Abstract** – *This paper presents the application of rule-based control on the multimode cricket bowling machine to create varying bowling deliveries. Rule-based control on the machine allows an easier imitation of the different deliveries utilized by the real cricket bowlers. This was achieved by studying the kinematic properties of the cricket bowling and designing the rule base to achieve the required trajectory. The corresponding rules had three inputs namely ball speed, side spin, and length whereas the outputs were motor rotational speed, motor rotational direction, and motor base orientation. The investigated rules were divided into two major groups; without-ball spin rules and with-ball spin rules. The first group was physically experimented and compared with simulation results via the ball's trajectory mathematical model whereas the later was only simulated. Both results showed the effect of the rules on the ball trajectories where there was good coherence with the kinematic data obtained from the bowling deliveries. However, the effect of the ball spin rules was relatively small in terms of magnitude due to the lower ball rotational velocity. Thus, improving the machine's capability by applying higher ball rotational velocity would augment the effect of the rules.*

***Keywords***: *Rules' simulation, ball trajectory, cricket bowling machine, kinematic, rule-based control.*

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## I. Introduction

### *A. Bowling Kinematics*

Rule-based control was applied on the multimode cricket bowling machine to control and vary the bowling deliveries with respect to the ball's velocity, spin axis, and spin direction. This allows for easier imitation of the different deliveries utilized by real cricket bowlers. Prior to the rule base design process, it was important to review the various bowling deliveries available to study their kinematic properties. Bowling deliveries could be broken down into two major categories; fast bowling and spin bowling. The former usually consisted of seam and swing bowling whereas the latter comprised of drift, top-spinner, flipper, leg break, off break, slider, and arm ball [1]. In this study, only spin bowling deliveries were considered. Fig. 1 illustrates the bowler's view of the cricket pitch with different bowling lengths. Bowling length referred to the longitudinal distance along the pitch from the bowler to the ball's impact location on the opposite end of the pitch.

Ball drift during flight is seen as a left or right trajectory curve as the ball travels towards the batsman. This is achieved by spin bowlers through the application of rotation about the vertical axis component to the ball. As a result, a force generated at the ball with respect to ball spin direction (Magnus effect) caused it to deviate sideways from the initial line of flight. In cricket, the trajectory line or bowling line referred to the lateral distance across the pitch which is divided into two regions namely off side and leg side. On the other hand, top and backspin bowling requires the bowler to apply spin about the lateral axis. A top spinner would have the ball dip faster towards the pitch and bounces harder whereas a backspin (flipper) would have the ball land closer to the batsman and bounces less. Tennis sport employed these type of ball spins regularly.

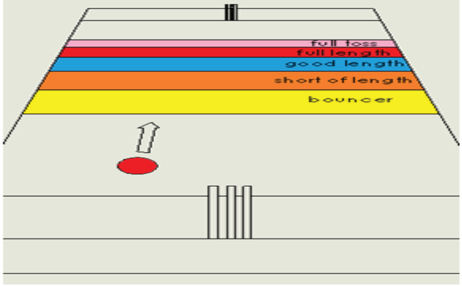


Fig. 1. Cricket bowling lengths.

Leg break is the standard bowling pattern used by a leg-spinner. Facing a right-handed batsman, the 'leg side' is on the left of the bowler whereas the 'off side' is on the right. This delivery essentially means that after the ball is bowled towards the leg side, it would hit the pitch and bounced or broke away from the initial line. The seam of the ball is required to face upwards in leg break as the ball is released to improve its spin rate and bounce. This helps in creating greater drift during ball flight which is often used to confuse the batsman. Furthermore, the seam is angled in the direction of the slip area. The reverse leg breaks bowling or known as 'googly' had the opposite effect of the traditional leg break. Instead of a break away from the leg side, the ball broke away from the off side towards the batsman despite the almost similar delivery action by the bowler for a leg spin. While the normal leg spin action had the ball released from the front of the hand, this bowling action had the ball released from the back of the hand to implement the opposite spin. Consequently, the batsman would be confused about the actual ball behaviour.

Off break refers to the bowling type where the ball broke away from the off side towards the leg side. Different from googly, this spin type had its own distinguishable bowling action. A stock delivery requires the seam to be angled in the opposite direction of a traditional leg spin. Furthermore, a clockwise spin is applied to the ball which allows the ball to bounce towards the leg stump. In contrast to a leg spinner's googly, doosra is the off spinner's solution to a delivery that uses similar action as a traditional off spin but with the ball deviating from the leg side towards the off side after bouncing off the pitch. Doosra, however, was more difficult to achieve compared to that of the googly.

The slider and arm ball was bowling deliveries unique to leg and off-spinners respectively. Both apply backspin to the ball but utilize their respective stock spin action. A slider also imparted some side spin during the delivery. Furthermore, the seam angle direction was opposite to that of a leg break during release. As a result, the batsman would have difficulty in differentiating between a backspin ball and a leg spin. While both the flipper and slider were essential backspin ball deliveries, the difference was in their respective grip form. Arm ball or also known as the floater was a straight ball bowled with an off-spin action. The objective of the delivery was to trick the batsman into anticipating an off-spin and play on the wrong line where in reality the ball is going straight. Moreover, the bowler could implement out-swing the position of the shiny surface on the ball arranged to face the leg-side.

The described spin bowling deliveries can be replicated by manipulating the spin axis orientation. For example, in drift bowling which can also be considered as side spin bowling, the spin axis is on the lateral axis of the ball whereas, for top and backspin bowling, the spin axis is on the vertical axis of the ball. For leg break and off-break bowling, the ball would spin about the longitudinal axis similar to rotation experience by a bullet along the gun's rifling. The spin of the ball about the said axis would cause it to bounce to the off side when rotating counter-clockwise from the bowler and vice versa. Aside from the ball's spin, the bowling deliveries also took into account the length and line of trajectory. Bowling length referred to the longitudinal distance of the ball trajectory along the pitch whereas bowling line referred to the lateral distance across the pitch. In drift bowling, the ball changes its line from one side of the field to the other whereas, in top/backspin, the length of the ball is affected. In a top spin, the faster dip caused shorter bowling length, in contrast to back spin as previously discussed.

The bowling velocities for cricket vary from 64 km/h up to 161 km/h. Fast bowlers can be categorised into fast, fast-medium, medium-fast, and medium where the typical velocity ranges are 141-161 km/h, 128-140 km/h, 113-127 km/h, and 97-111 km/h respectively [1, 2]. Spin bowlers, on the other hand, bowls within slow velocity range which is below 97 km/h. An important point to note was that the ball used in the experimental work had dimples and no seam, unlike an actual cricket ball. The reason was that most conventional cricket bowling machines or any machine of a similar class were not made to control the seam's orientation. This was also the case for the cricket bowling machine used in this study.

### *B. Mathematical Model*

The mathematical models describing the ball's trajectory were represented by (1), (2), and (3) [3, 4, 5, 6, 7]. The models took into account the effects of gravity, drag force, and lift force due to Magnus effect. Magnus effect occurs when a rotating object travels through a fluid. Depending on the direction fluid flow to the object's rotation, lift is generated. The acceleration in x, y, and z-axis was represented by $a_x$, $a_y$, and $a_z$ respectively

$$m_b a_x = -\frac{1}{2} C_D \rho A \left|\vec{V}\right| . \overrightarrow{V_x} - \frac{1}{2} C_L \rho A \left|\vec{V}\right| \left(\frac{v_z \omega_y - v_y \omega_z}{\omega}\right) \quad (1)$$

$$m_b a_y = -\frac{1}{2} C_D \rho A \left|\vec{V}\right| . \overrightarrow{V_y} - \frac{1}{2} C_L \rho A \left|\vec{V}\right| \left(\frac{v_x \omega_z - v_z \omega_x}{\omega}\right) \quad (2)$$

$$m_b a_z = -mg - \frac{1}{2} C_D \rho A \left|\vec{V}\right| . \overrightarrow{V_z} - \frac{1}{2} C_L \rho A \left|\vec{V}\right| \left(\frac{v_y \omega_x - v_x \omega_y}{\omega}\right) \quad (3)$$

The parameters involved were drag coefficient ($C_D$), lift coefficient ($C_L$), air density ($\rho$), cross-sectional area of ball ($A$), ball velocity ($V$), ball velocity magnitude ($\left|\vec{V}\right|$), ball angular velocity ($\omega$), ball radius ($r$), gravitational acceleration ($g$), and ball mass ($m_b$). The corresponding x, y, and z components of the ball's translational and angular velocity were represented by ($\overrightarrow{V_x}$), ($\overrightarrow{V_y}$), ($\overrightarrow{V_z}$), $\omega_x$, $\omega_y$, and $\omega_z$ respectively. The drag ($C_D$) and lift ($C_L$) coefficient were calculated based on (4), (5), and (6) respectively [3, 8]. The parameter u and $u_o$ represented the measured velocities at two different points in the ball's trajectory path whereas $D$ was the velocity decay rate.

$$C_D = 4mD/\rho\pi d^2 \quad (4)$$

$$D = -\frac{2}{s} ln\left(\frac{u}{u_0}\right) \quad (5)$$

$$C_L = 3.19\times10^{-1}\left[1-\exp\left(-2.48\times10^{-3}\omega\right)\right] \tag{6}$$

## II. Methodology

### A. Rule Base Design

Based on the kinematic study of the bowling delivery, the rule base was designed with respect to the limitations of the bowling machine's degree of freedom. The machine built for cricket bowling was capable of applying a rotation of the ball about the lateral and vertical axis only. However, the motor base as shown in Fig. 2 can be orientated to allow for the ball's spin axis to be slanted between the lateral and vertical axis by rolling the motor base 46 degrees about the machine's longitudinal axis as illustrated in Figure 3. This combination would produce balls with both top/backspin and side spin.

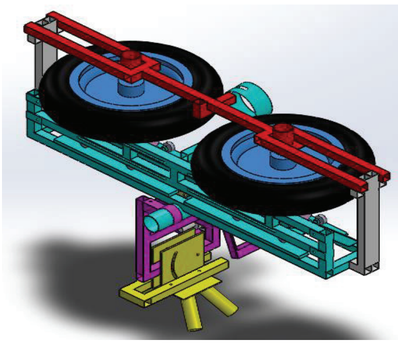

Fig. 2 Multimode cricket bowling machine

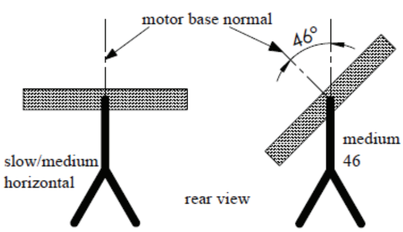


Fig. 3 Graphical representation of the machine's orientation from rear plan view

Three types of inputs governing the rules namely speed, side spin, and length were utilized in this study which corresponds to the kinematic studies of the cricket bowling deliveries. The output of the rules was the motor rotational velocity, motor rotational direction, and motor base orientation. The said orientation had to be done manually through the instructions to the user.

Each type consists of three different choices and therefore, twenty-seven possible combinations of inputs were produced. The rules created takes into account each input combination and their corresponding scenario or consequences and were written using IF/THEN statements [9]. The antecedent and consequent can be one variable or a combination of different variables connected together by either using AND/OR relationship. All twenty-seven rules were listed in Appendix 1.

The manipulation of ball length was achieved by applying top or backspin. Simultaneous application with side spin required the rotational axis to be slanted to the right or left. The controller achieved both spin application by requesting the user to ensure the position of the motor base at the specified angle from horizontal which could be seen in the listed rules. The motor rotational speed was varied using pulse wave modulation (PWM).

In the microcontroller, the PWM duty cycle is chosen for slow, medium, and fast speed mode were 50%, 70%, and 90% respectively. The PWM value for the slowest speed mode was chosen because the cricket bowling velocities had a range from 64 km/h to 161 km/h. The required wheel's angular speed corresponding to the 64 km/h bowling velocity was 1000 rpm for a wheel diameter of 0.34m.

PWM value range within the microcontroller was mapped from 0-100% to 0-220 decimal. The reason for not mapping 100% to 255 decimal was in consideration of the 15 % increase in duty cycle to one of the motors when the ball spin rule is fired under fast speed mode. Under the new mapping, 1000 rpm would corresponds to 50% duty cycle. Moreover, under fast speed mode, the motor that was given 105% PWM duty cycle would actually correspond to 253 in decimal. The rest of the duty cycle were chosen with increments of 20% to obtain three-speed modes. The corresponding duty cycles and decimal values are shown in Table I.

TABLE I
PWM DUTY CYCLES AND CORRESPONDING DECIMAL VALUES

| Duty cycle % | Decimal values |
|---|---|
| 50 | 110 |
| 70 | 154 |
| 90 | 220 |

### B. Ball Trajectory Simulation

Based on the mathematical model, several rules in the rule base were simulated to determine their effects on the ball's trajectory. Prior to simulation, it was important to measure the initial ball translational and rotational velocity. The rotational velocity of the ball from the cricket bowling machine can be estimated based on (7) which considered speed ratio between the ball and the wheel [10]. The speed ratio (SR) value was obtained from the ball's translational velocity experimentation. This parameter referred to ratio between the ball's linear/translational velocities to that of the wheel. For the experimentation done using the bowling machine, the ratio decreases as the wheel's angular velocity increases.

$$\omega_b = \frac{(S_{R1}v_1 - S_{R2}v_2)}{2r_b} \tag{7}$$

The angular speed of the wheels are controlled by PWM under 50 % (10.4 V), 70 % (14.4 V), and 90 % (18.4 V) duty cycles which represented slow, medium, and fast mode respectively. These PWM duty cycle values were based the relationship between cricket ball velocities and wheel's angular speed described previously. When applying the spin to the ball, there would be a 30% difference in the duty cycle between the two wheels. The calculated wheels' angular speed for slow, medium and fast mode with the duty cycle difference was [1430; 770] rpm, [1821; 1179] rpm, and [2100; 1500] rpm respectively. Moreover, the angular speed difference between the two wheels was maintained at about 600 rpm to produce the same ball spin velocity regardless of its direction and velocity during the design phase. Depending on which wheel was assigned with the larger angular speed, the ball would spin in the opposite direction.

## III. Results and Discussions

### *A. No Ball Spin Rules*

For the rules with no-ball spin, the simulation was performed at slow and medium ball velocity settings. Based on the measured launch angle and mean slow ball velocity, the calculated ball trajectory was compared to the measured value and tabulated in Table II for the slow ball and Table III for the medium ball. Furthermore, the Reynolds number, Re, for slow ball velocity of 17.53 m/s, was about $1.97 \times 10^5$ whereas for medium ball velocity was $2.22 \times 10^5$. Referring to studies made by [11, 12], the expected drag coefficient was approximately 0.2 for dimple golf ball whereas for new and used cricket balls, the values were 0.45 and 0.65 respectively. In the simulation, a drag coefficient of 0.4 was chosen based on the average samples of drag coefficients calculated using Equation 5. Moreover, the release height of the ball was measured at 0.82 m.

TABLE II
SLOW BALL BOWLING IMPACT LENGTH

| Distance, m | Re = $1.97 \times 10^5$ | |
|---|---|---|
| | $C_D$=0.4 | Measured |
| Mean | 12.06 m | 11.98 m |

TABLE III
MEDIUM BALL BOWLING IMPACT LENGTH

| Distance, m | *Re* = $2.22 \times 10^5$ | |
|---|---|---|
| | $C_D$=0.4 | Measured |
| Medium-horizontal | 14.62 m | 16.12 m |
| Medium-rolled | 12.33 m | 14.09 m |

### *B. Ball Spin Simulation*

Rules chosen for the simulation involved horizontal spin, vertical spin, or a combination of both under slow mode. As such, only Rule 1, 2, 10, 11, 12, 19, 20, and 21 from Appendix were simulated. Remaining ones were similar combinations at higher speed modes of which were determined to have a very low ball spin velocity due to the lower speed ratio. The corresponding estimated length and the line calculated also included the ball release angle previously measured.

The length is defined as the longitudinal bowling distance of the ball from the machine along the pitch on the first impact with the ground. Whereas, the line is defined as the lateral bowling distance across the pitch of the ball from centreline on first ground impact. A graphical representation of the ball spin for each rule is illustrated in Figure 4. The corresponding trajectory plots for the listed rules are shown in Figure 5, 6, 7, and 8, respectively. The neutral line in the said figures represented the ball trajectory without the spin when the motor base was rolled 46 degrees counter-clockwise for Rule 10 and 19 or 46 degrees clockwise for Rule 11 and 20. This served as the reference to demonstrate the rules' effect.

TABLE IV
SIMULATED RESULTS FOR THE BALL'S LENGTH AND LINE WITH RESPECT TO THE RULES

| Rule | Applied ball spin | Length, m | Line, m |
|---|---|---|---|
| 1 | Left spin | 11.90 | 0.08 |
| 2 | Right spin | 11.90 | -0.08 |
| 10 | Top spin and left spin | 10.13 | 1.08 |
| 11 | Top spin and right spin | 10.13 | -1.08 |
| 12 | Top spin | 6.89 | 0.94 |
| 19 | Back spin and right spin | 10.56 | 1.00 |
| 20 | Back spin and left spin | 10.56 | -1.00 |
| 21 | Back spin | 7.09 | 0.96 |

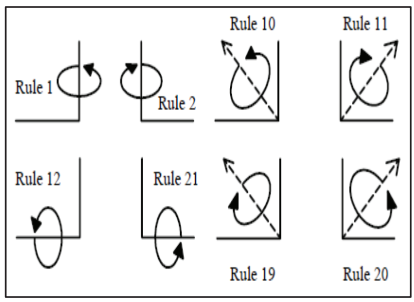


Fig. 4 Graphical representation of ball spin; dashed line arrow indicates resultant ball spin axis from machine's back plan view

In Rule 1 and 2, only side spin or rotation about the ball's z-axis was involved with the motor base at horizontal. The negative values in the simulation results represented deviations towards the right of the machine. From the table, it was concluded that under 818 rpm of side spin only, the ball's trajectory line deviated by 0.08 m without any change in length calculated earlier in this chapter. On the other hand, Rule 12 and 21 only deals with top and back spin respectively. Under those two rules, the motor base was rolled 90 degrees counter-clockwise and thus, the ball was expected to be released towards the left of the machine with an angle of 7.74 degrees from x-axis along the x-y plane. Since the ball did not launch upwards like in Rule 1 and 2, the calculated length was shorter. Moreover, Rule 21 had a longer length compared to Rule 12 because of additional upward force related to Magnus effect which reduced the downward acceleration of the ball. This was in contrast to Rule 12 which had top spin causing the ball to swerve downwards faster resulting in the shorter length.

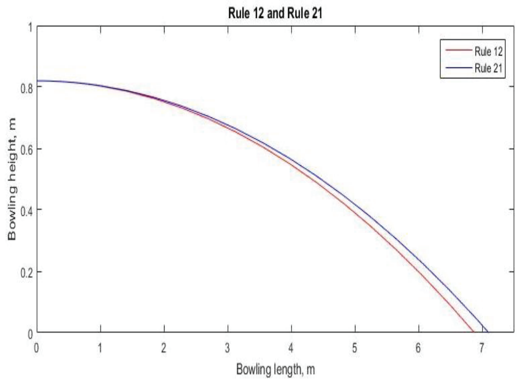


Fig. 5 Simulation trajectory plots: Rule 12 and 21; Side view plan

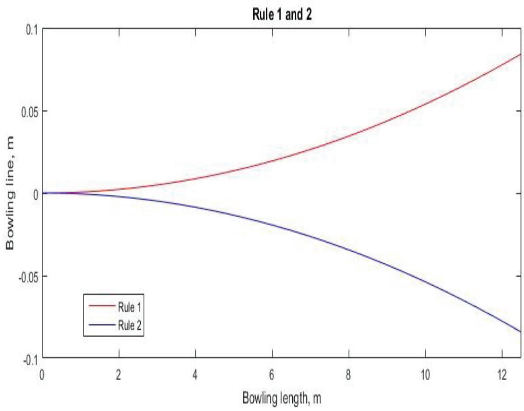


Fig. 6 Simulation trajectory plots: Rule 1 and 2; Top view plan

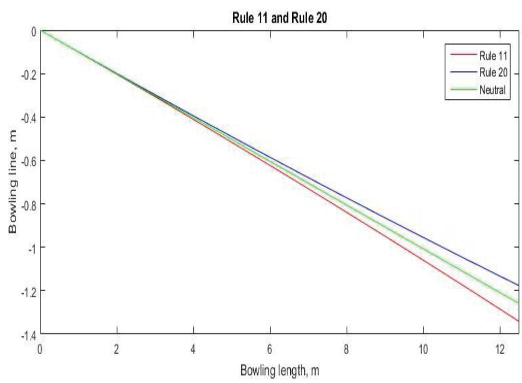


Fig. 7 Simulation trajectory plots: Rule 11 and 20; Top view plan

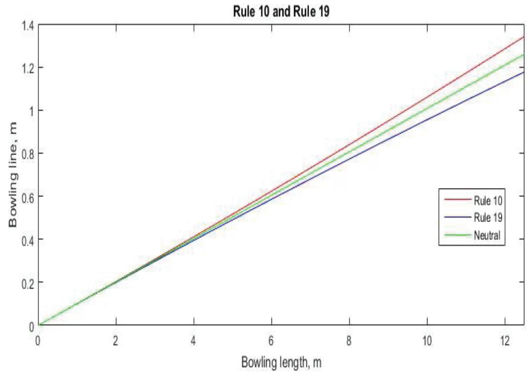


Fig. 8 Simulation trajectory plots: Rule 10 and 19; Top view plan

The dotted line indicated the ball release direction due to the initial release angle and motor base orientation. Application of both types of spins required the motor base to be rolled at an angle. Rule 10 and 11 dealt with the combination of top spin with left or right spin respectively whereas Rule 19 and 20 were opposite. In Rule 10, the motor base was rolled 46 degrees counter-clockwise. With the ball release vector pointing towards the left, the left spin component caused the ball to deviate further towards off-side. This was the opposite of Rule 11 that had the motor base rolled 46 degrees clockwise.

For Rule 19 and 20, the motor base was in the opposite position as Rule 10 and 11 respectively. This caused the ball to deviate in the opposite direction as its initial release vector which can be seen in its lower line deviation values as compared to Rule 10 and 11. At 46 degrees orientation, the ball release vector was resolved into its y-axis and z-axis components. Thus, the ball's release angle along the x-z plane was 5.49 degree. This caused the length calculated for those rules to be smaller than Rule 1 and Rule 2. Similar to Rule 21, Rule 19 and 20 had a larger length compared to their counterparts due to back spin with an average difference of 0.43 m.

Based on the results, some of the rules did not produce the intended results. For rule 19 and 20, it was designed to produce ball trajectory towards the leg side and off side respectively. The ball was not directed towards the centre line because of the ball release vector. During the design phase, all the rules were made assuming that the ball would be launched along the centreline. Additionally, the ball had small lift force which caused small line deviation. Lift force due Magnus effect was dependent on the object's translational and rotational velocity. While increasing the ball velocity would increase lift, the speed ratio relationship obtained for the current two-wheel bowling machine would cause the spin velocity to decrease. Therefore, modifications must be done to the machine to improve the speed ratio gradient. This would allow for greater ball translational and rotational velocity.

# IV. Conclusion

To conclude, the applied rule base on the multimode cricket bowling machine showed good coherence between the simulated ball trajectories to that of the studied bowling deliveries. However, for the ball spin rules, the magnitude of the changes made by the rules was low due to smaller lift force as a result of the lower ball rotational velocity. Improvements have to be done on the machine to enhance the said parameter.

The comparison between the measured and simulation results was only performed for the no-ball spin group. This was due to the vibration issue experienced by the machine when spin was applied which would affect the reliability of the tests. Thus, this issue must also be taken into consideration for the improvement in future experiments.

# Appendix

RULE BASE

| No. | Rules |
|---|---|
| **1** | IF speed is slow AND spin is left AND length is normal THEN motorA pwm is 65% AND motorB pwm is 35% AND advice motor base at horizontal. |
| **2** | IF speed is slow AND spin is right AND length is normal THEN motorA pwm is 35% AND motorB pwm is 65% AND advice motor base at horizontal. |
| **3** | IF speed is slow AND spin is nospin AND length is normal THEN motorA pwm is 50% AND motorB pwm is 50% AND advice motor base at horizontal. |
| **4** | IF speed is medium AND spin is left AND length is normal THEN motorA pwm is 85% AND motorB pwm is 55% AND advice motor base at horizontal. |
| **5** | IF speed is medium AND spin is right AND length is normal THEN motorA pwm is 55% AND motorB pwm is 85% AND advice motor base at horizontal. |
| **6** | IF speed is medium AND spin is nospin AND length is normal THEN motorA pwm is 70% AND motorB pwm is 70% AND advice motor base at horizontal. |
| **7** | IF speed is fast AND spin is left AND length is normal THEN motorA pwm is 105% AND motorB pwm is 75% AND advice motor base at horizontal. |
| **8** | IF speed is fast AND spin is right AND length is normal THEN motorA pwm is 75% AND motorB pwm is 105% AND advice motor base at horizontal. |
| **9** | IF speed is fast AND spin is nospin AND length is normal THEN motorA pwm is 90% AND motorB pwm is 90% AND advice motor base at horizontal. |
| **10** | IF speed is slow AND spin is left AND length is small THEN motorA pwm is 65% AND motorB pwm is 35% AND advice motor base 45deg CCW from horizontal. |
| **11** | IF speed is slow AND spin is right AND length is small THEN motorA pwm is 35% AND motorB pwm is 65% AND advice motor base 45deg CW from horizontal. |
| **12** | IF speed is slow AND spin is nospin AND length is small THEN motorA pwm is 65% AND motorB pwm is 35% AND advice motor base 90deg CCW from horizontal. |
| **13** | IF speed is medium AND spin is left AND length is small THEN motorA pwm is 85% AND motorB pwm is 55% AND advice motor base 45deg CCW from horizontal. |
| **14** | IF speed is medium AND spin is right AND length is small THEN motorA pwm is 55% AND motorB pwm is 85% AND advice motor base 45deg CW from horizontal. |
| **15** | IF speed is medium AND spin is nospin AND length is small THEN motorA pwm is 85% AND motorB pwm is 55% AND advice motor base 90deg CCW from horizontal. |
| **16** | IF speed is fast AND spin is left AND length is small THEN motorA pwm is 105% AND motorB pwm is 75% AND advice motor base 45deg CCW from horizontal. |
| **17** | IF speed is fast AND spin is right AND length is small THEN motorA pwm is 75% AND motorB pwm is 105% AND advice motor base 45deg CW from horizontal. |
| **18** | IF speed is fast AND spin is nospin AND length is small THEN motorA pwm is 105% AND motorB pwm is 75% AND advice motor base 90deg CCW from horizontal. |
| **19** | IF speed is slow AND spin is left AND length is big THEN motorA pwm is 65% AND motorB pwm is 35% AND advice motor base 45deg CW from horizontal. |
| **20** | If speed is slow AND spin is right AND length is big THEN motorA pwm is 35% AND motorB pwm is 65% AND advice motor base 45deg CCW from horizontal. |
| **21** | IF speed is slow AND spin is nospin AND length is big THEN motorA pwm is 35% AND motorB pwm is 65% AND advice motor base 90deg CCW from horizontal. |
| **22** | IF speed is medium AND spin is left AND length is big THEN motorA pwm is 85% AND motorB pwm is 55% AND advice motor base 45deg CW from horizontal. |
| **23** | IF speed is medium AND spin is right AND length is big THEN motorA pwm is 55% AND motorB pwm is 85% AND advice motor base 45deg CCW from horizontal. |
| **24** | IF speed is medium AND spin is nospin AND length is big THEN motorA pwm is 55% AND motorB pwm is 85% AND advice motor base 90deg CCW from horizontal. |
| **25** | IF speed is fast AND spin is left AND length is big THEN motorA pwm is 105% AND motorB pwm is 75% AND advice motor base 45deg CW from horizontal. |
| **26** | IF speed is fast AND spin is right AND length is big THEN motorA pwm is 75% AND motorB pwm is 105% AND advice motor base 45deg CCW from horizontal. |
| **27** | IF speed is fast AND spin is nospin AND length is big THEN motorA pwm is 75% AND motorB pwm is 105% AND advice motor base 90deg CCW from horizontal. |

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