STABILITY ANALYSIS OF CLIMBING ROBOTS USING ADAPTIVE INTELLIGENT CONTROL SYSTEM

1. INTRODUCTION

The steep rise in development of climbing robot research makes a strong foundation in almost all the application areas like cleaning, inspection, transportation and maintenance. This is because of the limited capabilities of human intervention with hazardous and unreachable fields of operation. Therefore, there is a growing need of developing climbing robot studies for adaptable applications with greater stability.

Presently, climbing robots are designed with multiple mechanism for adhesion and locomotion for its effect on stability and control of smooth traversing on specific surface. One of the most challenging tasks is to develop a proper adhesion mechanism to ensure that the robot system sticks to wall surfaces reliably without sacrificing mobility. The developed suction-based adhesion and drive wheel mechanism provide a better stability and robustness in terms of adaptive control by empowering climbing robots suits for various applications. This climbing robot also ensures to maneuver on different surface environments smoothly with adaptive intelligence in overcoming surface disturbances.

2. REVIEW OF LITERATURE

The climbing robots and its operations are broadly classified in use of various adhesion and locomotion techniques. The adhesion ensures the climbing robot adhering to the wall surface with mechanisms like atmospheric methods, magnetic methods, grippers and bio-inspired methods. The locomotion mechanism includes maneuvering capability such as wheel-based methods, tracked methods, legged methods, sliding and hybrid methods. The operations of climbing robots deal with inspecting surfaces and security surveillances, transporting in hazardous places were human intervention is not advisory and cleaning process for effectiveness and high reliability.

In the vast development of robotics and automation research, the field of climbing robots makes its path in challenges of adhesion and method of traversing. This resolves a research in design of climbing robot adhesion by ensuring proper mechanism such as suction based adhesion [1], [2]. The atmospheric thrust assisted climbing robot maintains its stability by maintaining a minimum gap from the surface of traversing [3]. The author Dominic Belter et al. used legged mechanism for maneuvering in different surfaces and rough terrains [4]. The use of legged methods provides greater adaptability control in various patterns of wall surfaces. For maintaining the stability of climbing robot in rough surface, the method of bio-inspired adhesive proves the better performance with low cost design [5]. Also, the method of passive suction cup with guide rail mechanism provides high mobility in attachment to the wall surface [6]. These climbing robots provides high stability in various surface conditions but lacks the advantageous of carrying high payload.

The authors Haydn Welch et al. analyzed to improve the payload capability by enabling magnetic wheel adhesive force methodology for climbing robots [7]. H Wang and A Yamamoto developed an electrostatic actuation with electro adhesion mechanism for climbing robots. This gives better solution in carrying high payload with less energy consumptions [8]. The major drawbacks in use of this mechanism is the limitation in surface oriented as the climbing robots cannot maneuver on non-ferromagnetic surfaces. The efficiency of using hybrid locomotion mechanism gives high reliability and mobility in maintaining the climbing robot without falling down at any instant [9]. Q Zhou and X Li developed a negative suction and wheel driven robot which ensures better performance in climbing robot stability and adaptiveness [10]. To enhance the stability, this research in climbing robot is employed with active suction sliding mechanism with adaptive intelligent control for maintaining the mobility in change of surface conditions.

2.1 RESEARCH GAP

The existing climbing robot development lacks the stability on various surface condition and also design is specific application oriented. The stability in terms of adaptiveness to various surface condition is still a limiting factor in the recently developed climbing robots. Still there is a compromising in stability and adaptiveness, which is not completely realized. The climbing robot with adaptive intelligent control system maintains the stability of climbing robot to suit different surface conditions. The proper intelligent control mechanism maintains the robot safety threshold condition by employing non-return safety suction rubber valves to stick on the surface of the wall in power supply failure.

2.2 OBJECTIVE

The main objective of the study is to design, develop and analyze the climbing robot stability on various surface conditions. The study includes kinematic and dynamic approach by using suction pressure generated chamber for adhering to the wall, individual drive wheel system for locomotion. The challenging task was to develop a climbing robot adhesion and its adaptiveness. The climbing robot with adaptive intelligent suction pressure control maintains the robot in maneuvering wall surface like glass, wood and semi constructed brick surface without falling down.

The following are the list of scope of research involved in achieving the objective.

1. Investigations on the controlled negative suction pressure developed inside the chamber of climbing robot.

2. Design, test and analyze the effect of controllability using different contours towards maintaining the stability of climbing robot with different shapes and surface conditions.
3. Modeling and simulation of the adaptive control algorithm for suction pressure change while subjected to different surface conditions.
4. Real-time implementation of the software and hardware for adaptive suction pressure control to overcome surface irregularities.

3. MATERIALS AND METHODS

The foremost aim in satisfying the objective of the research is development of climbing robot suitable for maneuvering in different wall surfaces. The broad classification of wall surfaces considered includes glass for analysis with slippery surface, wood for analysis with smooth and rough surface, semi-constructed brick wall to overcome surface irregularities and disturbances. The design and development of Multi-functional wall climbing robot (MWCR) depends mainly upon the stability by means of equal distribution of forces among the chamber. This design is the method of dimensional analysis, which maps equal classification of parameters involved in modelling MWCR. The three major parameters in design of MWCR is Dimensional Analysis, Simulation methods and Experimental analysis.

3.1 STABILITY ANALYSIS

The analysis of MWCR's stability depends upon the two extreme cases featuring robot's motion and adhesion behavior. The major factors while design of stability analysis is 1. Kinematic analysis of robot moving mechanism, 2. Limit equilibrium condition or Dynamic modelling and 3. Virtual robot simulator or simulation modelling for wall climbing robot traversing and adhesion forces.

In order to provide the position of MWCR in the work environment there is a necessity of two different coordinate system which defines the frames required for better stability of a wall climbing robot. The coordinate systems are Inertial reference frame system and axial frame system. The kinematic configuration of MWCR is shown in figure 1 depicting the stability of robot in maintaining its position and orientation. The inertial reference frame system is considered as the base frame of MWCR denoted as $\{x_{br}, y_{br}\}$ and the axial frame system is considered as the moving frame and is denoted as $\{x_m, y_m\}$.

Figure 1. Kinematic configuration of MWCR

The desired purpose of kinematic modelling is to represent the MWCR stability as a function of robot driving wheel velocity along with the dynamic and geometric parameters of the robot. The wheel configuration of MWCR is based on four individually driven motor wheel assembly. The kinematics of drive wheel and MWCR configuration is shown in figure 2.

Figure 2. Kinematic representation of wall climbing robot

Dynamic analysis of wall climbing robot includes the behavior of motion and the various forces acting on the wheel and the wall surface which affects the motion of MWCR. These also includes the energies of rolling resistance and the traversing speed associated with these motions.

4. RESULTS AND DISCUSSION

The most challenging aspect of stability in MWCR is the aerodynamic drag pressure controllability to suit various surface conditions and also overcome surface irregularities. Based on one dimensional continuity equation, the suction pressure difference between the surface and the MWCR chamber must be balanced with the gravitational force acting downwards. The design of MWCR consisting of suction chamber mounted with a suction motor and a ducted fan (impeller) assembly. This is used for generation of airflow velocity, Va and thereby pressure difference is developed between inside and outside of the chamber. For a specific time period the amount of air enters the duct fan is lesser than the amount of air exhausts. At steady state, when P_a decreases, the air pulled inside attains equilibrium that is given by $A_iV_i = A_oV_o$. Therefore, the velocity inside the chamber remains constant over the area A. In such condition when there is a change in area the velocity inside the chamber varies accordingly the pressure generated varies, $A_2 < A_1, V_{a_2} > V_{a_1}$ and $V_{a2} > V_{a_1}$, $P_2 < P_1$. The drop in chamber pressure is also a factor of MWCR wheel grip when comes in contact with surface material and moisture conditions. The Table 1 shows friction coefficients for wheel material to surface material combination and conditions.

Table 1. Total suction pressure with different surface disturbances

Material & Material combinations		**Surface conditions**	**Static μ_{static}**	**Kinetic (sliding) $\mu_{kinetic}$**
Plastic	Gypsum	Clean & Dry	0.2	0.11
Rubber	Stucco	Lubricated, Greasy & Rough	0.45	0.4
Polyurethane	Concrete	Dry, Rough & brick gaps	0.78	0.65

The design of Aerodynamic drag pressure depends upon the factors given by the amount of frictional and dynamic loss distributed inside the suction chamber and the resulting suction pressure. These two factors are related with distance H from the surface. For small H, suction pressure developed will be small and similarly for large H, suction pressure will converge to free flight equivalent based on Hovercraft principle and thereby reduces negative pressure. The total suction pressure developed inside the suction chamber is calculated and tabulated for the different surface distribution.

Table 2. Total suction pressure with different surface disturbances

Conditions	**Total suction Pressure, S_p**		
	No gap	With 1mm gap	With 2mm gap
Holding firmly	3.312	2.669	2.021
Dragging on surface	2.326	1.89	1.77
Fall-off (fail condition)	1.602	1.33	1.212

Investigation on Suction chamber shape and pressure generation

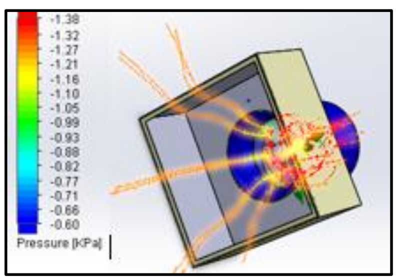
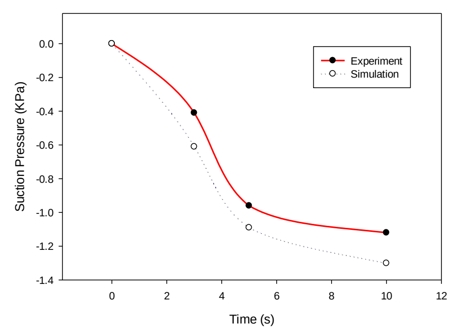
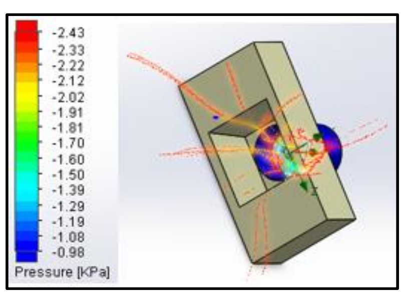
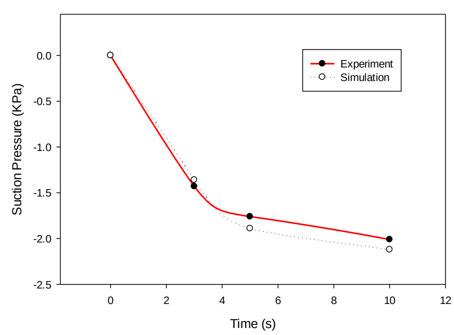
The 3-dimensional geometrical view and design of various shapes of suction chamber is modelled using Solidworks V19 CAD software. As per dimensional analysis, the suction motor with impeller is modelled separately with the same CAD tool and assembled the housing of suction chamber for analysis of

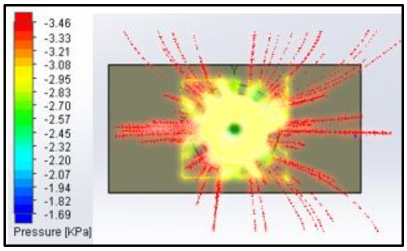
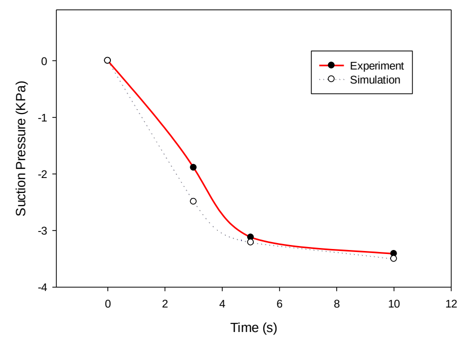
MWCR. The major criteria of analysis in CAD software is the meshing and pressure flow analysis. The analysis is carried out with same software additional tool named FLU-EFD, which is the preprocessor, bundled with Solidworks version 2019. The investigation is performed for different shapes of suction chamber contour and the suction pressure developed inside the suction chamber is analyzed. To analyze the suction pressure generated inside the suction chamber, the suction motor is set to run at a constant speed. The simulation parameters are defined for solver as “steady state”, the solving approach as “segregated”, the algorithm as “implicit”, the type of flow as “K-Epsilon”, and the material as air. The simulation is done for three different suction chamber contours namely, with fully open rectangular contour, with open trapezoidal contour and trapezoidal contour suction chamber with bottom restrictor. The suction motor speed is set to 5000 rpm with impeller diameter of 50 mm. The detailed boundary conditions with analytical view for Solidworks Flu-EFD Simulation are worked out.

A comparative investigation is carried out with 3 different cases of suction chamber contours for the aerodynamic behaviour to identify suction pressure generation. Simulation results show that in the case of suction chamber with fully open rectangular contour generates suction pressure of -1.3 KPa. In case 2 with open trapezoidal contour suction chamber, suction pressure of -2.1KPa is observed. In case 3 with suction chamber with bottom restrictor, suction pressure of -3.6 KPa is observed.

The experimental results show that in the case of suction chamber with fully open rectangular contour suction pressure of -1.12 KPa is observed. In case 2 with open trapezoidal contour suction chamber, suction pressure of -2.0KPa is observed. In case 3 with suction chamber with bottom restrictor, suction pressure of -3.5 KPa is observed. The theoretical, simulation and experimental results are found to be very close. It is obvious that the attraction force will be the highest when the chamber is operated with a bottom restrictor. The detailed boundary conditions with analytical view for Solidworks Flu-EFD Simulation are shown in Table 3. For the analysis of simulation, dynamic analysis of MWCR is considered as Gypsum board for case 1 wall material, for case 2 the Stucco high pressure plate with roughness 0.42% friction is used and for case 3 concrete brick wall with 0.4mm gap.

Table. 3. Suction pressure analysis: Simulation vs Experiment for different contours

<table>
<tr><td colspan="3">Boundary Conditions
Impeller Dimensions: S_d = 50mm, H=140 mm, Material: FRP
Atmospheric pressure - 101.3 KPa, Gravity -9.81 m/s^{2,} Fluid – Air, Rotational velocity - 5000 rpm</td></tr>
<tr><td></td><td>Suction Chamber pressure analysis</td><td>Results: Simulation vs Experiment</td></tr>
<tr><td>Case 1
Wall
(Gypsum)
0.26% sfd</td><td>
</td><td>
</td></tr>
<tr><td>Case 2
Rough wall
(Stucco HP)
0.42% sfd</td><td>
</td><td>
</td></tr>
</table>

Case 3 **Brick pattern** **(Stucco HP+0.4mm)** **0.42% sfd**		

Experimental Analysis

The figure 3 shows the view of the experimental prototype operating on brick wall. The developed prototype MWCR consists of a suction motor, a suction chamber with bottom restrictor, drive motor, pressure sensor and Arm processor with Wi-Fi module. Figure 4 shows the rear view of the robot with bottom restrictor. The self-weight of the robot is 1Kg. and it can handle a payload of 0.6 Kg.

The suction chamber is fabricated using FRP material. The suction pressure developed inside the suction chamber is monitored using ZSE 40 SMC pressure sensor. The acquired data is processed by the arm processor and transmitted through Wi-Fi module to the computer. Li Po 11.1V, 4500 mAh battery is used as a power source. The suction chamber is fabricated with dimensions of 200mm length, 120mm breadth and 120mm height. The suction motor with 50mm diameter impeller is operated at a constant speed of 5000 rpm. The experimental study is performed with three different suction chamber contours namely, with fully open rectangular contour, with open trapezoidal contour and with bottom restrictor.

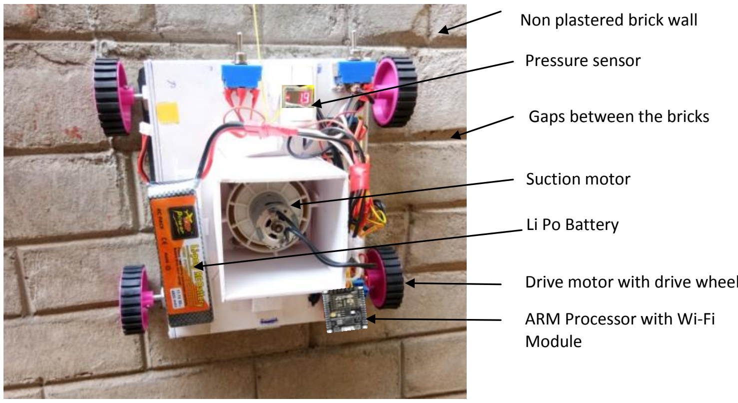


Figure 3. Experimental setup

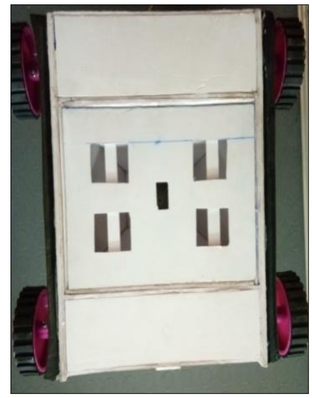


Figure 4. Novel bottom restrictor

Table. 4. Simulation and Experimental samples for running continuously for 20min

Case 1: Suction chamber with fully Open Rectangular Contour

conditions	**Suction Chamber Pressure (KPa)**									
	Static			**Dynamic**				**Experimental analysis**		
	Simulation (computation time: 20min) 10 samples			Simulation (computation time: 40min) 10 samples				Running Time 20 min		
	Min.	Max.	Avg.	Min.	Max.	Avg.	V_d (m/s)	Holding	Drag	Drive speed (m/s)
Case 1 Hollow	0.6	1.38	1.10	0.45	1.25	0.9	0.01	1.0	0.8	0.011
Smooth wall (Gypsum) 0.26% sfd	0.4	1.376	1.10	0.66	1.32	1.16	0.09	1.1	0.8	0.012
	0.56	1.379	1.09	0.62	1.33	1.12	0.012	1.0	0.9	0.012
	0.55	1.377	1.1	0.58	1.26	1.01	0.014	1.0	0.8	0.01
	0.6	1.39	1.11	0.59	1.30	1.01	0.014	1.1	0.9	0.011
	0.58	1.379	1.07	0.61	1.27	1.12	0.011	1.0	0.8	0.011
	0.59	1.411	1.04	0.65	1.24	1.10	0.016	1.0	0.8	0.012
	0.49	1.22	1.10	0.59	1.32	0.9	0.012	1.0	0.9	0.01
	0.61	1.38	1.10	0.6	1.29	1.10	0.012	1.1	0.9	0.011
	0.59	1.378	1.09	0.62	1.25	0.9	0.012	1.1	0.9	0.012

Case 2: Suction chamber with open Trapezoidal contour

conditions	Suction Chamber Pressure (KPa)									
	Static			**Dynamic**				**Experimental analysis**		
	Simulation (computation time: 20min) 10 samples			Simulation (computation time: 40min) 10 samples				Running Time 20 min		
	Min.	Max.	Avg.	Min.	Max.	Avg.	V_d (m/s)	Holding	Drag	Drive speed (m/s)
Case 1 Trapezoidal	0.98	2.43	1.91	0.94	2.22	1.82	0.009	1.9	1.6	0.012
Rough wall (Stucco HP) 0.42% sfd	0.82	2.35	1.90	0.91	2.26	1.82	0.011	1.9	1.5	0.01
	0.89	2.39	1.94	0.96	2.34	1.98	0.01	2.1	1.7	0.011
	0.95	2.41	1.96	0.95	2.30	1.91	0.012	1.9	1.5	0.012
	0.94	2.39	1.89	0.91	2.29	1.89	0.011	1.8	1.4	0.009
	0.92	2.34	1.91	0.88	2.19	1.81	0.012	2.0	1.7	0.011
	0.88	2.39	1.91	0.91	2.31	1.82	0.012	1.9	1.6	0.012
	0.89	2.41	1.95	0.93	2.27	1.83	0.012	2.1	1.7	0.012
	0.96	2.43	1.91	0.89	2.21	1.79	0.012	2.0	1.7	0.011
	0.97	2.378	1.89	0.92	2.34	1.81	0.012	1.9	1.6	0.012

Case 2: Suction chamber with Novel Bottom Restrictor contour

conditions	Suction Chamber Pressure (KPa)									
	Static			**Dynamic**				**Experimental analysis**		
	Simulation (computation time: 20min) 10 samples			Simulation (computation time: 40min) 10 samples				Running Time 20 min		
	Min.	Max.	Avg.	Min.	Max.	Avg.	V_d (m/s)	Holding	Drag	Drive speed
Case 1 Restrictor	1.39	3.46	2.70	1.37	3.41	2.79	0.009	3.4	2.9	0.01
Brick pattern (Stucco HP+0.4mm) 0.42% sfd	1.38	3.44	2.78	1.39	3.41	2.79	0.012	3.3	2.7	0.012
	1.37	3.39	2.81	1.34	3.35	2.66	0.01	3.4	2.8	0.011
	1.39	3.45	2.72	1.35	3.35	2.69	0.01	3.1	2.4	0.012

	1.41	3.52	2.82	1.38	3.41	2.79	0.011	2.9	2.1	0.01
	1.41	3.49	2.82	1.39	3.43	2.81	0.012	2.9	2.1	0.01
	1.39	3.41	2.79	1.39	3.41	2.79	0.012	3.1	2.6	0.011
	1.40	3.41	2.79	1.38	3.4	2.76	0.01	3.3	2.8	0.012
	1.38	3.33	2.69	1.39	3.41	2.79	0.01	3.4	2.7	0.012
	1.39	3.42	2.81	1.39	3.41	2.79	0.011	3.3	2.6	0.011

Investigation on MWCR material deformation-Stress and strain analysis

The most important step in analysis is the detection of failure and fault tolerance capability of the material when subjected to load applied on particular material. To analyze this capability computational fluid dynamic (CFD) study is performed. To implement CFD, Ansys r17.2 version workbench is used. Ansys CFD is a powerful simulation workbench, which performs qualitative analysis to provide quantitative predictions on load interaction with material changes and fault tolerance rate. The computational time is minimal when compared with existing Flu-EFD in Solidworks. The material used for MWCR is thick re-inforced fiber, which provides high friction and better stability in maneuvering on vertical wall surface. The limit in material deformation is analyzed using stress and strain factor by the help of Ansys CFD. Stress and Strain factor plays a major role in design of any material application analysis.

Particularly, in design aspect the changes in material deformation because of high pressure in flow leads to dysfunction of MWCR. The material study is done for circumstances like maximum holding stress when total suction force is applied to the robot chamber. Fluent predicts the amount of strain in fault cases where the climbing robot traction changes and stability loses. The results of Ansys CFD is compared with the real-time experiment to study the dynamic changes in MWCR. The strain analysis observed using Ansys strain simulation was compared with experimental prototype of the MWCR. This analysis was done by providing additional suction pressure drop through manual disturbance of 1mm to 2 mm thickness of gap between the MWCR chamber with the surface. Particular comparison was done to test the stability of the MWCR in vertical surface in case of disturbances and strain because of traction change thereby affecting the mobility. The results were seeming to be quite similar with that of the simulation observation.

Investigation on Stability analysis of MWCR Aerodynamic drag virtual simulation

The set of dynamics and kinematics parameters of wall climbing robot that were obtained in previous section have been modelled using Solidworks v2019 and simulated the dynamics using Solidworks motion dynamic solver. The results obtained for the dynamic solver gives the encoder angular information of the wall climbing robot traversing from horizontal to vertical denoted as φ_{θ}. The aerodynamic drag pressure modelling is performed using computational fluid dynamics (CFD) toolbox named Flu-EFD in Solidworks V19. The simulation window is based on the suction chamber modelling of MWCR. The closed loop dynamic modelling of suction pressure balances the wall climbing robot to overcome minimum 1 mm and maximum of 2 mm surface disturbances.

The 3D modelling of wall climbing robot is performed using Solidworks MBD v3.6 (model-based definition) based on mathematical analysis of solid wall climbing robot position and orientation. The dynamics is developed using motion analysis in Solidworks v19.

The simulation of Solidworks dynamic modelling is analysed using wall climbing robot placed on a 3D plane surface with adiabatic wall surface friction coefficient of 0.25.

The Computational fluid dynamic simulation for motion analysis of wall climbing robot overcoming 1 mm and 2 mm of surface disturbance was performed for the period of 100 seconds. The result depicts the robot total suction pressure generated or leaked with 20s-time interval. The results depict the applied disturbance to the wall climbing robot and corresponding suction pressure drop was observed. The amount of suction pressure was found to be around 2 KPa, 1.8 KPa and 1.69 KPa for normal, 1mm and 2mm disturbances respectively.

Investigation on Adaptive intelligent controller for traction and autonomous control of MWCR

The remotely operated wall climbing robot consists of an embedded development board (Ni-myRIO) as a real-time controller capable of acquiring sensor data and control remotely. The myRIO is kept standalone with wall climbing robot and it continuously sends robot signals wirelessly. The closed-loop control diagram of adaptive intelligent control system for stability with safety suction rubber cups is shown in figure 5.

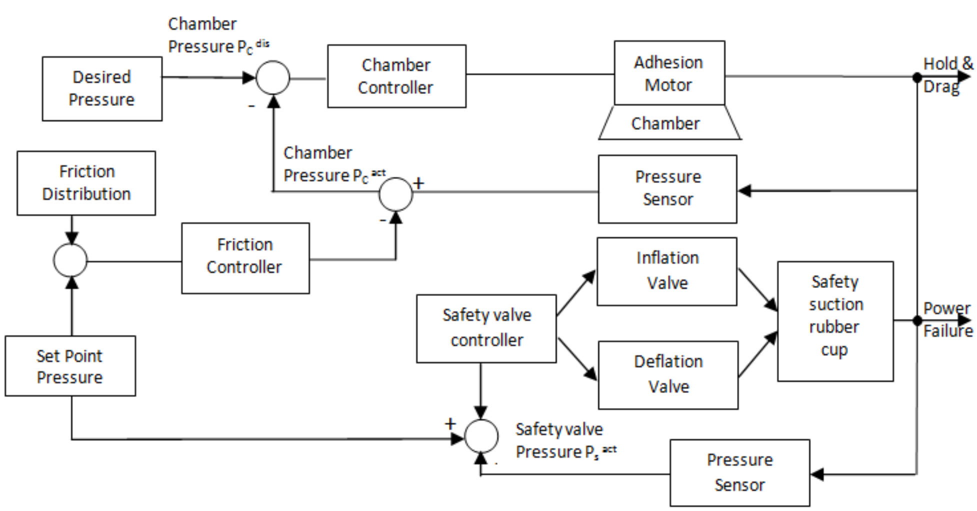


Figure 5. Closed-loop Adaptive control system of MWCR

Front end and programming is done through LabVIEW environment and the control communication works with Wi-Fi based shared variable concept. The Control operation of MWCR using shared variables works through a GUI created through Ni Dashboard app installed in handheld Tablet PC. A dedicated control algorithm is programmed to maintain the required negative pressure inside the suction chamber to adhere with the wall and functions to maintain the mobility of the climbing robot. The feedback from the pressure sensors is used to maintain the negative pressure by varying the speed of the suction motor through handheld Tablet PC.

The hardware parts in development of MWCR features three major assembly units named adhesion, locomotion and control units. Adhesion unit comprises of a suction motor assembled with impeller. Locomotion unit comprises of 4 individually driven wheel mechanism carrying geared DC motor with motor driver. Control unit comprises of Wi-Fi enabled Ni-myRIO embedded development board. The MWCR control panel acquires pressure sensor data and provides necessary information on input variables to generate and control required suction pressure. The control of suction pressure is applicable only when the MWCR is subjected to disturbances and where the high suction pressure gives the MWCR to stick firmly on vertical wall surfaces. Based on closed-loop control by acquiring angular information using accelerometer and pressure sensor data, The MWCR navigation panel provides the decision on navigation and stability control of wall climbing robot. The control dashboard in handheld Tablet consists of a slider bar, a navigation pad, and pressure and accelerometer sensor display indicators. Using the navigation pad, the traction mobility can be achieved by sliding or changing the direction of MWCR.

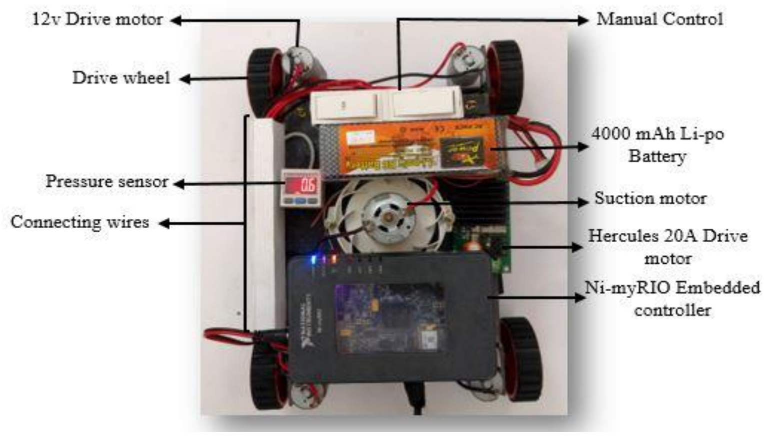


Figure 6. MWCR Experimental Prototype with Ni-myRIO

4.1 CONCLUSION

The suction pressure analysis generated inside the suction chamber of the MWCR was evaluated theoretically, then analyzed with different analytical software's and experimentally validated. The proposed methodology of employing a bottom restrictor with a particular pattern at the bottom of the suction chamber lead to large increase in suction pressure development ranging between150–175%.

The MWCR is tested with various materials which includes Plastic foam sheet material, 1.5 mm thick Aluminum sheet, 1mm thick metal sheet and Fibre-reinforced plastic (FRP) materials. Simulation and experimental result of static and dynamic stress and strain performance depicts that using FRP material leads to less self- weight and thereby increased payload capability.

An experimental setup was designed and developed for traversing stability on various surface condition like glass, smooth, rough concrete brick walls. The performance of real-time adaptive control using NI-myRIO ensures intelligent mechanism to adapt surface frictional change. The complete MWCR power was optimized by providing standalone battery with Human machine interface (HMI) system.

5. SUMMARY

The overall investigation is to design and develop a multifunctional wall climbing robot (MWCR) capable of traversing on different wall surfaces. The adaptiveness of climbing robot ensures proper stability and mobility in maneuvering smoothly without compromising surface friction. The remotely operated handheld control system implementation provides robot stability for different test applications.

6. FUTURE DIRECTION

The suction pressure generated by the brushed DC suction motor may lead to periodic maintenance. As a future work, Brushed DC motor could be replaced with brushless DC motor to overcome maintenance cost.

The MWCR material analysis can be further analyzed for higher payloads and to withstand at higher temperature ranges 150-200 degree Celsius.

7. REFERENCES

1. Muthukumaran, G. and Ramachandraiah, U. (2016) Development and Analysis of Robotic Sliding Suction Cup System for Wall Climbing Applications, vol. 9, *Indian Journal of Science and Technology*, 9(1); 1-7.

2. Cho, K.H., Jin, Y.H., Kim, H.M., Moon, H., Koo, J.C., and Choi, H.R. (2017) Multifunctional Robotic Crawler for Inspection of Suspension Bridge Hanger Cables: Mechanism Design and Performance Validation, *IEEE/ASME Transactions on Mechatronics*, 22(1); 236–246.

3. Dino Mehanovic, David Rancourt, and Alexis Lussier Desbiens (2019) Fast and Efficient Aerial Climbing of Vertical Surfaces Using Fixed-Wing UAVs, *IEEE Robotics and Automation Letters*, 04(1); 1435–1443.

4. Dominik Belter (2019) Efficient Modeling and Evaluation of Constraints in Path Planning for Multi-legged Walking Robots, *IEEE Access*, 99(1); 107845–107862.

4. Jinfu Liu., Linsen Xu, Shouqi Chen, Hong Xu, Gaoxin Cheng, Tao Li and Qingfeng Yang. (2019) Design and Realization of a Bio-inspired Wall Climbing Robot for Rough Wall Surfaces, *Springer Nature*, 1(3); 47–59.

6. Dingxin Ge, Yongchen Tang, Shugen Ma, Matsuno, Takahiro and Ren Chao. (2020). A Pressing Attachment Approach for a Wall-Climbing Robot Utilizing Passive Suction Cups, *Robotics*, 9(26); 1-16.

7. Haydn Welch (2019). Analysis of Magnetic Wheel Adhesion Force for Climbing Robot, *Journal of Mechatronics and Robotics*, 3(1); 534-541.

8. Wang H. and Yamamoto A. (2017) Analyses and Solutions for the Buckling of Thin and Flexible Electrostatic Inchworm Climbing Robots, *IEEE Transactions on Robotics*, 33(4) 889–900.

9. Bykov N V. (2019) A Mathematical Model of the Locomotion Mechanism of a Mobile Track Robot with the Magnetic-Tape Principle of Wall Climbing, *IEEE Journal of Machinery manufacturing and Reliability*, 48(3) 74–84.

10. Q. Zhou and X. Li (2016) Design of wall-climbing robot using electrically activated rotational-flow adsorption unit, *IEEE/RSJ International Conference on Intelligent Robots and Systems*, Korea, 5758–5763.

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1. Navaprakash N., Uppu Ramachandraiah, & G. Muthukumaran, “Information Based Remote Control system for Climbing Robot Applications.” International Journal of Engineering Trends and Technology, Vol. 68, issue3, pp 6-11, 2020.
2. Navaprakash N., Uppu Ramachandraiah, & G. Muthukumaran, “Design & Development of Suction based Wall-Climbing System.” International Journal of Mechanical and Production Engineering Research and Development, Vol. 10, issue2, pp 537-550, 2020.

3. N. Navaprakash, Uppu Ramachandraiah, G. Muthukumaran, V. Rakesh, and Ashutosh Pratap Singh, “Modeling and Experimental Analysis of Suction Pressure Generated by Active Suction Chamber Based Wall Climbing Robot with a Novel Bottom Restrictor,” Procedia Computer Science, vol. 133, pp. 847–854, 2018.
4. N. Navaprakash, Uppu Ramachandraiah, G. Muthukumaran, V. Rakesh, and Ashutosh Pratap Singh, “Live Demonstration: Wall Climbing Robot Using Fuzzy Based Adaptive Control System” IEEE Sensors, New Delhi, India, 2018.
5. N. Navaprakash, Uppu Ramachandraiah, G. Muthukumaran, “Design and Development of Adaptive Intelligent control system for Reservoir based wall climbing robotic system” Indonesian Journal of Electrical Engineering and Computer Science**. Scopus indexed.**
6. N. Navaprakash, Uppu Ramachandraiah, G. Muthukumaran, “Real-time Dynamic modular modelling, Analysis and Experimental verification of climbing robot for stability” IEEE Transactions on mechatronics. **Scopus & SCI indexed. (*Manuscript under review).**
7. **Doctoral symposium** presentation on titled “Suction chamber analysis of Multifunctional Wall Climbing Robot using Solidworks” in 4th International conference on **Advances in Robotics (AIR 2019)** organized by The Robotic Society (RSI) in IIT, Madras.
8. **Conference Paper** presentation on titled **“**Information based Remote control system using Ni-myRIO for climbing robot applications**.”** in IEEE International Conference on Electrical, Communication, Electronics, Instrumentation and Computing (ICECEIC 2019), conducted by SCSVMV, Kancheepuram, Tamilnadu, India.