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Robotic arm powered by artificial intelligence for agricultural work

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TABLE OF CONTENTS

Dedications	3
Acknowledgments	4
List of tables.....	13
List of figures	14
List of abbreviations	17
List of appendices	18
GENERAL INTRODUCTION	19
I. Literature review	25
CHAPTER 1: Agriculture Fundamentals	25
1.1 Introduction.....	25
1.2 Weed control methods in agriculture	25
1.2.1 Introduction to weed control	25
1.2.2 Definition of Weed Control	26
1.2.3 Types of weeding.....	27
1.3 Chemical weed removal	28
1.3.1 Thermal weed control	29
1.3.2 Other Weed control methods	31
1.4 Current Challenges in Weed Management	34
2 Harvesting methods in agriculture	35
2.1 Classification of Harvesting Systems	35
2.1.1 Manual Harvesting.....	35
2.1.2 Mechanical Harvesting	36
2.2 Challenges in Fruit Harvesting: Balancing Labor, Cost, and Crop Quality	37
Conclusion	37
2 CHAPTER 2: ROBOTIC ARM MODELING IN AGRICULTURE	40
2.1 Introduction to Robotic Arm Modeling for Agricultural Applications	40
2.2 Definition of robots and robotic arms.....	41
2.2.1 Automation.....	41
2.2.2 Hard Automation	41
2.2.3 Programmable Automation.....	41
2.2.4 Autonomous Automation.....	41
2.2.5 Definition of Robots.....	41
2.2.6 Definition of a Robotic Arm	42
2.3 Manipulator Classifications	42

2.3.1	Cartesian Manipulators	42
2.3.2	Articulated Manipulators.....	43
2.3.3	SCARA Manipulators.....	44
2.3.4	Spherical Manipulators.....	45
2.3.5	Cylindrical Manipulators.....	45
2.4	Degrees of freedom in robotic arms	46
2.4.1	Degrees of Freedom (DOF) in Mechanical Systems	46
2.4.2	General DOF Equation for a System	46
2.4.3	Cartesian to Polar Coordinates Conversion.....	47
2.4.4	Holonomic Constraint Equation	47
2.4.5	Grübler's Formula	47
2.5	Workspace of robotic arms	48
2.5.1	Workspace	48
2.5.2	Load Capacity.....	49
2.5.3	Speed	49
2.5.4	Repeatability and Accuracy	49
2.6	Kinematics of robotic arms.....	50
2.6.1	Definition of kinematics in robotics:	50
2.6.2	Homogenous Transformation Modelling Convention.....	50
2.6.3	Forward Kinematics (FK).....	51
2.6.4	Denavit-Hartenberg (D-H) Parameters.....	53
2.6.5	Inverse Kinematics (IK)	53
2.6.6	Differential Kinematics	58
2.7	Dynamic Modeling in Robotic	61
2.7.1	The Three Main Formalisms for Modeling Manipulator Dynamics.....	61
2.8	Trajectory Planning.....	63
2.8.1	Cartesian Space Trajectory Planning	63
2.8.2	Joint Space Trajectory Planning.....	63
2.9	Force Control	64
2.10	Robotic arm components	65
2.11	Anatomy of a Robot.....	65
2.11.1	Mechanical components	65
2.11.2	Electrical and Electronic Components.....	70
2.11.3	Challenges of Robotic in Agriculture	72
Conclusion:		74

Chapter 3: AI and Machine Learning in Agriculture	77
Introduction to AI	77
2.1 What is Artificial Intelligence?	77
2.2 AI Vocabulary	77
2.3 AI and Machine Learning in Agriculture	78
2.4 Artificial Intelligence in Weed Management.....	79
2.4.1 Integration of AI with IoT, UAVs, and Field Robots	79
2.4.2 Autonomous Robotic Weed Control Systems	79
2.4.3 Drivers of AI Adoption in Weed Management	79
2.4.4 Challenges in Autonomous Weed Control	80
2.5 Artificial Intelligence in Harvesting.....	80
2.5.1 The Role of Robotic Harvesting Systems	80
2.5.2 Machine Vision for Harvesting	80
2.5.3 Challenges in Autonomous Harvesting Systems	81
2.6 The Role of Actuators in Harvesting Robots.....	81
2.7 Challenges in AI and Automation for Agriculture.....	81
2.7.1 A IoT: The Integration of AI and IoT in Agriculture.....	82
2.7.2 Challenges in Implementing AI in Agriculture	82
2.7.3 AI's Potential in Addressing Global Agricultural Challenges.....	83
Conclusion	83
II. Materials and Methods	86
1.1 Introduction.....	86
1 Chapter 1: Structure and Design Considerations	87
1.1 Overview of Robotic Arm Parts	87
1.1.1 Description.....	87
1.1.2 Design Specifications and Dimensions	88
1.1.3 Design Tools:.....	89
1.2 Structural Elements	90
1.2.1 Finger Gripper & Gear	90
1.2.2 Base of the Robotic Arm	92
1.2.3 Cycloidal Gearbox 1:10	92
1.2.4 Gripper Joint	93
1.2.5 Link.....	93
1.2.6 Nema17 Motor Mount	94
1.2.7 Rotative Base	94

2	Chapter 2: Kinematic and Dynamic Modeling	97
2.1	Introduction	97
2.1.1	Kinematic Equations for Robotic Motion	97
2.1.2	Work Space:.....	97
	Results	98
2.1.3	Denavit-Hartenberg Parameters	98
2.1.4	Forward Kinematics	99
2.1.5	Inverse Kinematics.....	99
2.2	Robotic Arm Dynamic Analysis	100
2.2.1	Dynamic Model Development.....	100
2.2.2	Lagrangian Formulation.....	100
2.2.3	Numerical Validation	101
2.2.4	Performance Characteristics	101
2.2.5	Agricultural Applications	102
3	Chapter 3: Component Selection	104
3.1	Hardware :	104
3.1.1	Motor and Actuator Selection:.....	104
3.1.2	Raspberry Pi 4 Model B	109
3.1.3	ESP32-S3	113
3.1.4	Raspberry Pi Camera Module 3:	114
3.1.5	Power Supply Unit	116
3.1.6	4S Battery: 14.8V (four cells, calculated as $4 \times 3.7V$)	116
3.1.7	LM2596 DC-DC Voltage Regulator.....	117
3.1.8	Rotary Encoders.....	117
3.1.9	Cooling System	118
3.1.10	Connectivity Components	119
3.2	Circuit Design	120
3.2.1	Circuit Design Tool.....	120
3.2.2	The system's circuit schematic design :.....	122
4	Software Development and Control Algorithms	123
4.1	Control Algorithms	123
4.1.1	Introduction.....	123
4.1.2	Motion Planning	125
4.1.3	Simulation Example	126
4.2	Coding Tools	128

4.2.1	Visual Studio Code	128
1	Discussion of Results	131
1.1	Kinematic Performance:	131
1.2	Dynamic Behavior:.....	132
1.3	Component Validation:.....	133
1.4	Software Efficacy:	133
1.4.1	Algorithm Analysis for Motion Planning: A*, PRM, and RRT	133
1.4.2	Comparative Analysis and Final Thoughts.....	137
1.5	Limitations due to Material Constraints and Future Work	138
1.5.1	Context and Challenge:.....	138
	The robotic arm’s performance was constrained by material and component limitations:	138
1.5.2	Future Work and Next Steps:	138
1	Business Plan	141
1.1	Executive Summary	141
1.2	The team.....	141
1.2.1	Skills and experiences of team members	141
1.2.2	Shared goals and vision	142
1.2.3	Advisory support.....	142
1.3	The project.....	143
1.3.1	Mission.....	143
1.3.2	Vision	143
1.4	Value Proposition	143
1.5	Marketing Strategy	144
1.5.1	Target Audience.....	144
1.5.2	Key Strategies	145
1.5.3	Sales and Distribution.....	146
1.5.4	Measuring Success.....	146
1.6	Porter Analysis.....	147
1.7	PESTEL Analysis.....	148
1.8	SWOT Analysis	149
1.8.1	Key Success Factors (KSFs).....	149
1.9	Project launch schedule.....	152
1.9.1	Initial Research and Development.....	152
1.9.2	Detailed Design and Algorithm Development	152
1.9.3	Purchasing Materials	152

1.9.4	Construction and Assembly of the Prototype	152
1.9.5	Optimization and Technical Adjustments	152
1.9.6	Field Testing.....	152
1.9.7	Data Analysis and Final Review.....	152
1.9.8	Production Preparation	153
1.9.9	Marketing Strategy and Commercial Launch.....	153
1.10	Financial Review	153
1.11	Investments	154
1.11.1	Total payroll.....	155
1.11.2	External expenses.....	156
1.11.3	Cash flow statement.....	157
1.12	Offer prices	157
1.12.1	Basic Precision System.....	157
1.12.2	Advanced Treatment System	158
1.12.3	Harvesting and Weeding Robot.....	158
1.12.4	Why Choose Our Rental Options?	158
1.13	Key Performance Indicator (KPI)	158
General conclusion		162
Bibliographic references:		164
Appendix1 : Full Circuit Schematic of the Robotic Arm System.....		173

ABSTRACT :

This study develops a 4-DOF robotic arm to address agricultural challenges—labor shortages, environmental impact, and food demand—by combining kinematic modeling, dynamic analysis, and AI automation. The system achieved ± 2.5 mm positional accuracy within a 60 cm workspace using optimized kinematics, enabling precision weed removal and harvesting. Dynamic analysis using Lagrangian mechanics quantified torque (1.47–2.94 N·m) and energy use (100–175 W), validated under field-like conditions. Vision systems and path-planning algorithms (A*, PRM) achieved 92% success in cluttered simulations, while regenerative energy recovery (18%) supported sustainability. Challenges included actuator thermal limits and computational delays, yet modular design and reduced chemical reliance highlighted scalability. Future directions focus on resilient hardware, efficient algorithms, and hybrid energy solutions for real-world deployment. This work advances autonomous farming systems, balancing precision, productivity, and ecological stewardship to enhance food security in climate-vulnerable contexts.

Key Words:

Agricultural Robotics, 4-DOF Robotic Arm, Precision Weed Control, Kinematic Modeling, Dynamic Analysis (Lagrangian Mechanics), Denavit-Hartenberg Parameters, Inverse Kinematics, Machine Vision (Raspberry Pi Camera), Path-Planning Algorithms (A*, PRM), Regenerative Energy Recovery, Sustainable Agriculture, Autonomous Harvesting, Modular Robotic Design, Edge-AI Optimization, Hybrid Energy Systems, Computational Latency, Thermal Limitations in Actuators, Food Security, Environmental Stewardship, Climate-Resilient Farming

ملخص :

تتناول هذه الدراسة تطوير ذراع روبوتي رباعي الدرجات (4-DOF) لمعالجة التحديات الزراعية مثل نقص العمالة، والآثار البيئية، والطلب المتزايد على الغذاء، من خلال دمج النمذجة الحركية، والتحليل الديناميكي، والأتمتة الذكية. حقق النظام دقة في تحديد المواقع تصل إلى ± 2.5 مم ضمن مساحة عمل نصف كروية (60 سم) باستخدام معلمات دنافيت-هارتنبيرغ المحسنة، مما مكن من إزالة الأعشاب الضارة بدقة وحصاد المحاصيل الحساسة. كشف التحليل الديناميكي (بناءً على ميكانيك لاغرانج) عن عزم دوران يتراوح بين 1.47–2.94 نيوتن.متر واستهلاك طاقة (100–175 واط) تحت ظروف تحاكي البيئة الحقلية. حققت أنظمة الرؤية الحاسوبية (كاميرا راسبيري باي) وخوارزميات تخطيط المسار (A*) ، (PRM) نجاحاً بنسبة 92% في بيئات محاكاة معقدة، بينما أظهر استرداد الطاقة المتجددة (18%) إمكانات لدعم الاستدامة. على الرغم من تحديات مثل القيود الحرارية في المحركات وتأخيرات الحوسبة، أكد التصميم المعياري والاعتماد المحدود على المواد الكيميائية على قابلية التوسع. تركز التطويرات المستقبلية على تعزيز المرونة الهيكلية) مثل محركات BLDC عالية العزم، وتحسين الكفاءة الخوارزمية عبر شبكات عصبية خفيفة الوزن، وأنظمة طاقة هجينة للنشر العملي. تسهم هذه الأبحاث في تطوير أنظمة زراعة مستقلة توازن بين الدقة، الإنتاجية، والحفاظ على البيئة، لدعم الأمن الغذائي في ظل التغيرات المناخية والنمو السكاني العالمي.

الكلمات المفتاحية: الروبوتات الزراعية، ذراع روبوتي رباعي الدرجات، التحكم الدقيق في الأعشاب الضارة، النمذجة الحركية، التحليل الديناميكي (ميكانيك لاغرانج)، معلمات دنافيت-هارتنبيرغ، استرداد الطاقة المتجددة، الزراعة المستدامة، الحصاد الذاتي، أنظمة الطاقة الهجينة، الأمن الغذائي.

Résumé

Cette étude développe un bras robotique à 4 degrés de liberté (4-DDL) pour relever les défis agricoles—pénurie de main-d'œuvre, impact environnemental et demande alimentaire—en combinant modélisation cinématique, analyse dynamique et automatisation intelligente. Le système a atteint une précision de positionnement de $\pm 2,5$ mm dans un espace de travail hémisphérique de 60 cm grâce à des paramètres Denavit-Hartenberg optimisés, permettant une lutte précise contre les mauvaises herbes et une récolte délicate. L'analyse dynamique (mécanique lagrangienne) a quantifié le couple (1,47–2,94 N·m) et la consommation énergétique (100–175 W), validés dans des conditions proches du terrain. Les systèmes de vision artificielle (caméra Raspberry Pi) et les algorithmes de planification de trajectoire (A^* , PRM) ont atteint 92 % de réussite dans des simulations d'environnements encombrés, tandis qu'une récupération d'énergie régénérative (18 %) a souligné le potentiel de durabilité. Malgré des défis comme les limites thermiques des actionneurs et les retards computationnels, la conception modulaire et la réduction des intrants chimiques ont démontré une scalabilité prometteuse. Les travaux futurs visent à renforcer la robustesse matérielle (moteurs BLDC à haut couple), optimiser les algorithmes via des réseaux neuronaux légers, et intégrer des systèmes énergétiques hybrides pour un déploiement pratique. Cette recherche contribue à des systèmes agricoles autonomes, alliant précision, productivité et préservation écologique pour renforcer la sécurité alimentaire face aux changements climatiques et à la croissance démographique.

Mots-clés : Robotique agricole, bras robotique 4-DDL, lutte contre les mauvaises herbes, modélisation cinématique, analyse dynamique (mécanique lagrangienne), paramètres Denavit-Hartenberg, récupération d'énergie, agriculture durable, récolte autonome, systèmes énergétiques hybrides, sécurité alimentaire.