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Low-Cost Assistive Robotic Arm for Independent Feeding in a Home Environment

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Abstract

Assistive feeding robots can reduce caregiver dependence, but cost, complexity, and safe deployment remain barriers to home use. This study presents a low-cost, modular feeding prototype that integrates Raspberry Pi 4 high-level processing, Arduino low-level actuation, a six-servo mechanical assembly with four joints active in the standard feeding sequence, HC-SR04 distance sensing, a USB camera, and an ESP8266-based monitoring subsystem. The feeding task was implemented as eight commanded configurations (six forward and two return steps) and analyzed in MATLAB. The active joints covered commanded ranges of 100-140° (Servo 1), 80-180° (Servo 2), 80-175° (Servo 3), and 0-180° (Servo 4), corresponding to spans of 40°, 100°, 95°, and 180°, respectively; Servos 5 and 6 remained at 0° in the analyzed sequence. Functional bench tests confirmed execution of the documented food-transfer sequence and operation of the sensing and communication subsystems. Because the available record contains commanded rather than measured encoder trajectories, tracking-error, repeatability, cycle-time, and collision-force claims are not made. The prototype therefore establishes a reproducible low-cost platform for subsequent closed-loop trajectory control, vision-based mouth localization, quantitative safety validation, and user trials.

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Keywords: assistive robotics, feeding robot, low-cost robotic arm, embedded control, human–robot interaction, home assistance, Degrees of Freedom (DOF).

ذراع آلية مساعدة منخفضة التكلفة للتغذية المستقلة في بيئة منزلية

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الملخص

تقدم هذه الدراسة نموذجًا أوليًا منخفض التكلفة لذراع آلية مساعدة تهدف إلى تمكين الأشخاص ذوي الإعاقة الحركية من تناول الطعام بصورة أكثر استقلالية في البيئة المنزلية، وتقليل اعتمادهم على مقدمي الرعاية .يعتمد النظام على حاسوب Raspberry Pi 4 لتنفيذ مهام المعالجة والتحكم عالية المستوى، ولوحة Arduinoلتنفيذ مهام التحكم منخفضة المستوى، إلى جانب منظومة ميكانيكية تضم ست محركات مؤازرة، تُستخدم أربعة منها لتنفيذ تسلسل حركات التغذية المحدد. كما يشتمل النظام على مستشعر الموجات فوق الصوتية HC–SR04لقياس المسافات، وكاميرا USBللمراقبة البصرية، ووحدة ESP8266للاتصال والمراقبة اللاسلكية .يتكون تسلسل الحركة من ثماني وضعيات تحكم محددة مسبقًا، تشمل ست خطوات لتنفيذ حركة التغذية وخطوتين للعودة . وأظهر التحليل باستخدام برنامج MATLABأن نطاقات الزوايا المأمور بها للمحركات المؤازرة الأربعة الفعالة تراوحت بين 100و140 درجة للمحرك الأول، وبين 80و180 درجة للمحرك الثاني، وبين 80و175 درجة للمحرك الثالث، وبين 0و180 درجة للمحرك الرابع، في حين بقي المحركان الخامس والسادس عند زاوية صفر درجة طوال تسلسل الحركة المدروس .أظهرت الاختبارات الوظيفية قدرة النموذج الأولي على تنفيذ تسلسل حركات نقل الطعام إلى موضع التغذية، إلى جانب التشغيل الوظيفي لوحدات الاستشعار والاتصال .ونظرًا إلى أن البيانات المتاحة تقتصر على زوايا الحركة المأمور

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بها، دون توافر قياسات فعلية راجعة من مشفرات مواضع المحركات، لم تتضمن الدراسة تقييمًا كميًا لدقة تتبع المسار، أو قابلية تكرار الحركة، أو زمن دورة التغذية، أو قوى التصادم .وتخلص الدراسة إلى أن النموذج المقترح يمثل منصة هندسية أولية منخفضة التكلفة وقابلة للتطوير، يمكن الاستفادة منها مستقبلًا في تطبيق تقنيات التحكم ذي الحلقة المغلقة، وتحديد موضع فم المستخدم باستخدام تقنيات الرؤية الحاسوبية، وإجراء اختبارات كمية لتقييم السلامة والأداء، فضلًا عن تنفيذ تجارب عملية بمشاركة المستخدمين للتحقق من كفاءة النظام وملاءمته للاستخدام المنزلي.

الكلمات المفتاحية :الروبوتات المساعدة؛ التغذية المستقلة؛ الأذرع الروبوتية منخفضة التكلفة؛ التحكم المضمن؛ التفاعل بين الإنسان والروبوت؛ المساعدة المنزلية؛ درجات الحرية.

1-Introduction

Loss of upper-limb function may make eating dependent on caregiver assistance. Assistive feeding robots seek to improve independence through task-specific manipulation and accessible human–robot interfaces. Liu et al. [1] developed a low-cost voice-operated feeding platform, while Mashrur et al. [2] investigated a six-degree-of-freedom (DOF) manipulator supported by depth cameras. Choi et al. [3] combined food-acquisition estimation with face-recognition-based interaction, and Varga et al. [4] presented a wheelchair-mounted, 3-D-printed feeding arm. These studies establish the feasibility of robotic feeding while revealing trade-offs among autonomy, perception, affordability, portability, and safety validation. More broadly, assistive mechatronic systems benefit from modular design and integration of sensing and control [6], [7]. This study addresses the practical integration of a home-oriented feeding prototype using affordable hardware, predefined motion commands, environmental sensing, smartphone interaction, and auxiliary monitoring. The distributed controller builds on established approaches to embedded actuation and process supervision: digital PID control of a low-cost CNC plotter illustrates a relevant pathway for motion-control refinement [11], whereas smart-incubator monitoring [12] and microcontroller-based

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industrial process supervision [13] illustrate complementary sensing and monitoring architectures. These are related engineering precedents, not experimental evidence of feeding accuracy or user safety. The present work evaluates functional integration and commanded joint motion; autonomous mouth localization, measured closed-loop tracking, and clinical-grade monitoring are outside its demonstrated scope.

The specific contributions are:

1) A distributed low-cost architecture separating Raspberry Pi high-level functions from Arduino servo/sensor control.
2) A six-servo assistive-arm implementation in which four servos execute the documented feeding motion and two remain inactive in the analyzed sequence.
3) An eight-step feeding command sequence and MATLAB-based quantitative analysis of commanded joint ranges and step-to-step angular changes.
4) Integration of ultrasonic/camera environmental sensing, smartphone interaction, and an ESP8266 monitoring subsystem in one home-oriented prototype.
5) A clear validation boundary that separates demonstrated functional feasibility from future requirements for encoder-based accuracy, repeatability, cycle-time, force, and user-safety measurements.

2-Literature Review

Recent assistive-feeding studies increasingly emphasize perception, intuitive user interaction, safe motion, and operation outside controlled laboratories [1-5]. In contrast, table 1 presents a prototype which uses predefined joint commands and low-cost electronics as a reproducible development platform rather than a fully autonomous feeding solution. Related research on assistive mechatronics [6], [7], communication interfaces [8], embedded health sensing [9], [10], digital motion control [11], and monitoring systems [12], [13] provides relevant technical context, although these applications do not directly establish feeding performance.

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Table 1. Comparison of representative assistive-feeding systems

Study	Platform / control	Perception / interaction	Reported focus	Gap relative to this work
Liu et al. [1], 2020	4-DOF feeding arm	Voice recognition	Low-cost food selection and feeding	Different interaction; no integrated home-monitoring layer
Mashrur et al. [2], 2023	Off-the-shelf 6-DOF manipulator	Two depth cameras; vision	General feeding tasks and validation	Higher hardware/perception complexity
Choi et al. [3], 2023	Meal-assistance robot	Face recognition; acquisition-point estimation	Asian-food acquisition and UI	More autonomous perception than current prototype
Varga et al. [4], 2024	Wheelchair-mounted 4-DOF, 3-D printed, Arduino	Safety sensors	Cost-oriented modular feeding assistance	Wheelchair-specific architecture
Gordon et al. [5], 2024	Portable robot-assisted feeding system	User-in-the-loop / variable autonomy	Adaptability, safety, portability	Greater autonomy and mature user-centered deployment
Present work	Six servos; 4 actives in analyzed sequence; Raspberry Pi + Arduino	HC-SR04, USB camera, smartphone; monitoring sensors	Low-cost integrated home prototype and command analysis	Requires measured feedback and quantitative safety/user validation

The contribution is therefore an integrated, affordable prototype combining actuation, sensing, communication, and monitoring with transparent command-level analysis. Unlike systems offering advanced visual perception or adaptive planning [2], [3], [5], the present implementation is a foundation for future validation, not a demonstration of equivalent autonomy or superior performance.

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3-Methodology

3.1-System Architecture

The system uses a distributed embedded-control architecture. Figure 1 shows that the Raspberry Pi 4 supports camera acquisition, application-level processing, and communication, while Arduino issues low-level servo commands and interfaces with local hardware. This division of responsibilities is consistent with the modular embedded-control approach used in low-cost motion platforms [11] and sensing-oriented systems [12], [13]. The mechanical prototype has six installed servo channels. Four channels (Servos 1–4) vary during the documented feeding sequence; Servos 5 and 6 remain commanded at 0°. A fixed commanded angle does not imply that a physical joint is absent or mechanically immobilized. The diagram is interpreted as the intended architecture; quantitative closed-loop tracking is not claimed without measured joint feedback.

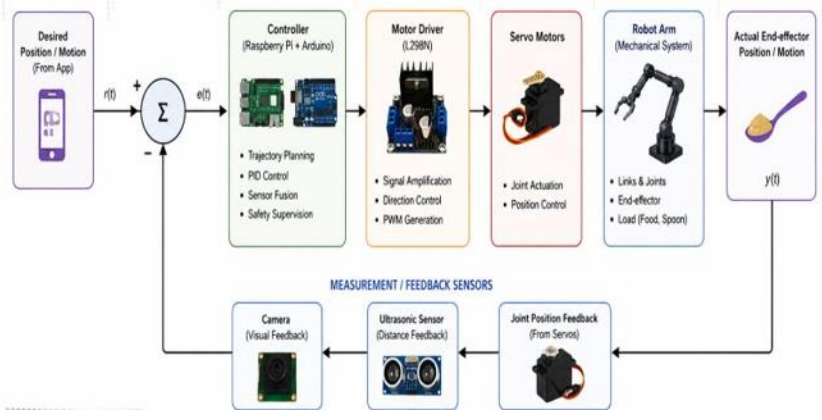


Figure 1. Functional architecture of the assistive robotic system.

3.2-Hardware and Mechanical Design

The arm structure was produced using 3D printing, providing a low-cost and easily modifiable mechanical platform. The 3-D printed arm model used as the mechanical platform is shown in Figure 2. Moreover, the table 2 shows the Hardware specification and quantity which is used in this study.

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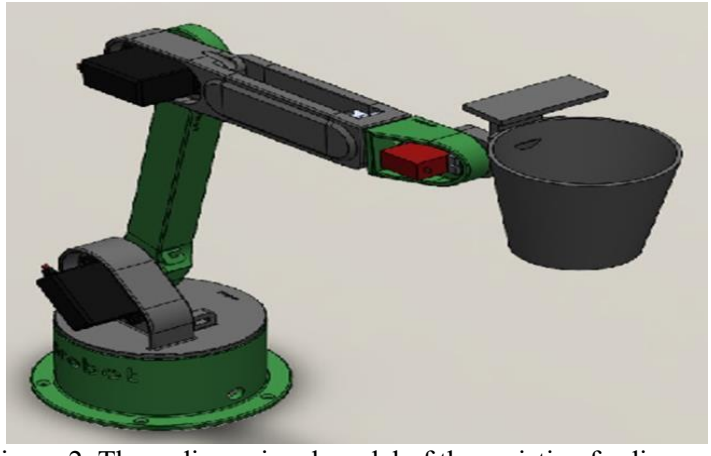


Figure 2. Three-dimensional model of the assistive feeding arm

Table 2. Hardware specification and quantity

Component	Model / type	Role/specification used in study	Qty.
Single-board computer	Raspberry Pi 4	High-level processing, camera, communication	1
Microcontroller	Arduino	Low-level servo and sensor control	1
Servo motors	Hobby positional servos	Six installed channels; Servos 1-4 active in analyzed feeding sequence	6
Ultrasonic Distance sensor	HC-SR04	Ultrasonic obstacle/distance sensing	1
Camera	USB camera	Visual monitoring / future mouth localization	1
Wireless controller	ESP8266	Auxiliary wireless sensor subsystem	1
Pulse-oximetry sensor	MAX30100	Engineering heart-rate/SpO2 monitoring; not clinical-grade	1
IMU	MPU6050	Motion monitoring	1
Temperature sensor	DS18B20	Temperature monitoring	1

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Component	Model / type	Role/specification used in study	Qty.
Motor driver	L298N	Auxiliary mini-pump drive	1
Mechanical structure	3-D printed arm	Low-cost modifiable arm structure	1
Power subsystem	ATX supply + DC/DC step-down	System power conversion	1 set

For the HC-SR04 ultrasonic sensor, the nominal distance is calculated from the echo round-trip time as $d = v_{air}\,\Delta t/2$, where v_{air} denotes the speed of sound in air and Δt is the measured round-trip delay. The factor of one-half accounts for the outward and return propagation paths. Because no calibrated distance-sweep dataset is available, this relation is presented as the measurement principle rather than as a validated accuracy result.

3.3-Communication and Control

Universal Asynchronous Receiver/Transmitter (A Universal Asynchronous Receiver/Transmitter (UART) connection links Raspberry Pi and Arduino, while I²C can interface compatible sensors; such serial protocols are widely used in embedded communication architectures [8]. The servo controller receives desired joint-angle commands. For joint i, tracking error would be defined as the difference between the desired and measured angle as given in equation 1:

$$e_i(t) = \theta_{i,d}(t) - \theta_{i,m}(t) \qquad (1)$$

Equation (1) defines a possible feedback-control metric, not an experimentally calculated error. The available record includes commanded positions but no synchronized measured joint-angle trajectories. Consequently, tracking RMSE, settling time, overshoot, and repeatability cannot be quantified. Digital PID control demonstrated in a low-cost CNC plotter [11] motivates a future feedback-control implementation, but the CNC results must not be transferred to this feeding robot without new measurements.,

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3.4-Feeding Motion Sequence

Figure 3 illustrates the individual commanded servo profiles, which is represented by eight discrete commanded configurations: six forward feeding steps and two return steps. MATLAB was used to examine the commanded angle of each servo and the differences between consecutive commands. Only Servos 1–4 vary in this recorded sequence; Servos 5 and 6 remain at 0°. These data describe the reference motion, not the measured trajectory, joint velocity, or end-effector position as shown in figure 4 and table 3.

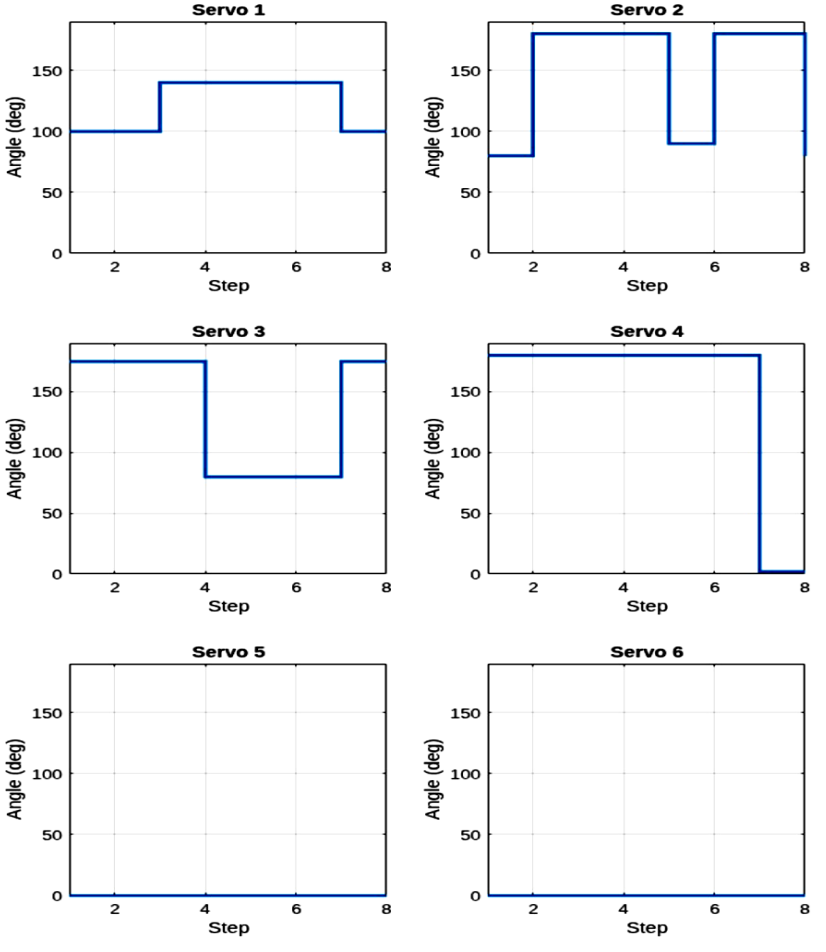


Figure 3. Individual commanded servo profiles for the eight-step feeding sequence.

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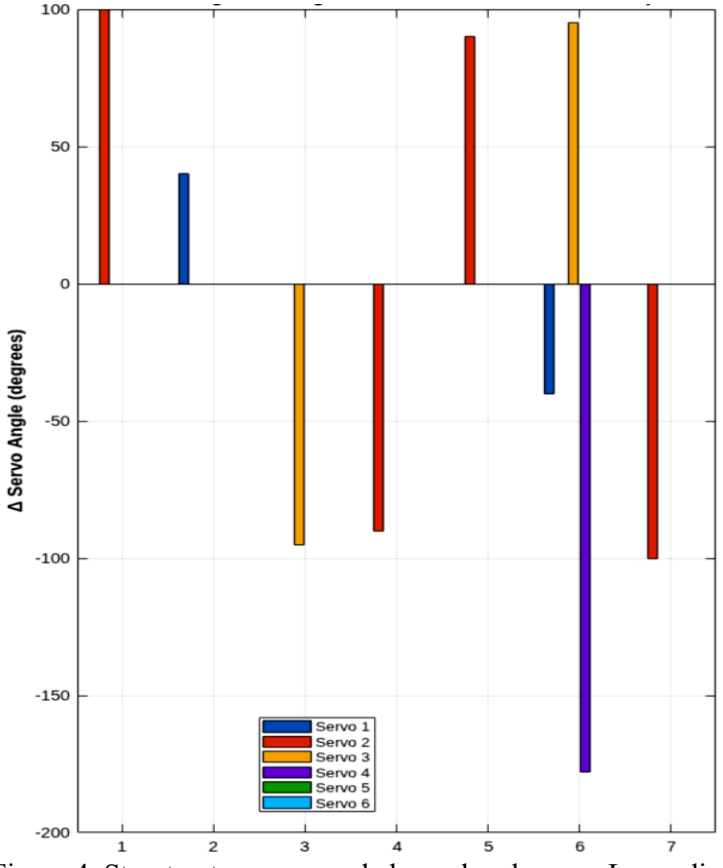


Figure 4. Step-to-step commanded angular changes. Large discrete changes identify transitions that should be smoothed in future trajectory control.

Table 3. Quantitative command-level motion summary

Servo	Minimum command	Maximum command	Command span	Status
1	100°	140°	40°	Active
2	80°	180°	100°	Active
3	80°	175°	95°	Active
4	0°	180°	180°	Active
5	0°	0°	0°	Inactive in sequence

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Servo	Minimum command	Maximum command	Command span	Status
6	0°	0°	0°	Inactive in sequence

3.5-Experimental and Validation Procedure

The available study record documents functional bench checks of motion, sensing, user interaction, environmental operation, and safety-related behavior. However, it does not include a complete trial log specifying repetitions, test durations, participant numbers, calibrated reference instruments, distance sweeps, or contact-force measurements. Table 4 therefore distinguishes observed functional behavior from quantitative outcomes that have not been established. This distinction is important when interpreting auxiliary monitoring devices, as integration alone does not establish clinical measurement accuracy [9], [10], [12].

Table 4. Validation matrix and evidence boundary

Test item	Input / condition	Evaluation criterion	Evidence available	Status in this paper
Motion sequence	Eight predefined joint configurations	Sequence executes and returns	Command record + prototype operation	Functional feasibility only
Ultrasonic sensing	Object present in sensor field	Distance/obstacle output responds	Functional study record	Qualitative; no calibrated error curve
Camera	USB camera connected to Raspberry Pi	Image acquisition available	Functional study record	Qualitative
Controller communication	Raspberry Pi-Arduino UART	Commands exchanged without loss during demonstration	Functional study record	Qualitative
Mobile interface	User command through	Command/response observed	Functional study record	Qualitative

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Test item	Input / condition	Evaluation criterion	Evidence available	Status in this paper
	smartphone layer			
Safety	Feeding motion + obstacle awareness	No unsafe contact during demonstration	General study record	Not a quantitative safety validation
Tracking accuracy / repeatability	Commanded vs measured joint angle over repeated trials	RMSE, max error, SD, settling time	Not recorded	Required future experiment
Feeding-cycle time	Repeated complete cycles	Mean ± SD cycle time	Not recorded	Required future experiment
Collision force	Contact/near-contact tests	Peak force below defined threshold	Not recorded	Required future experiment
Human-subject usability	Representative users	Success rate + validated usability metric	Not recorded	Outside current evidence

4-Results and Discussion

4.1-Prototype Implementation and Functional Results

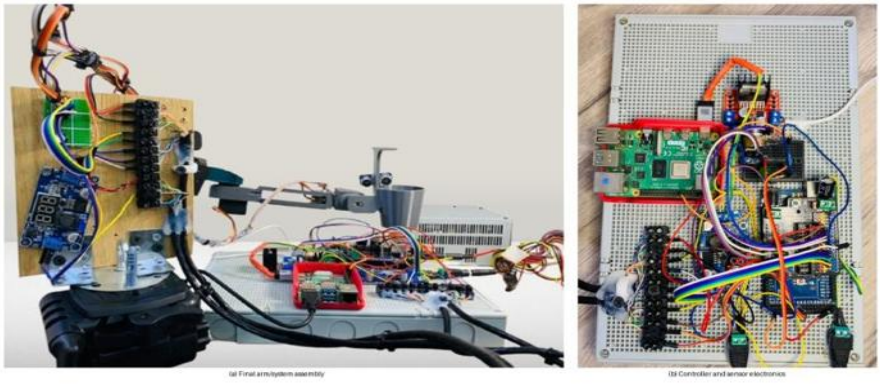


Figure 5. Final arm assembly and controller/sensor electronics used in the prototype.

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The prototype integrates the robotic arm, Raspberry Pi, Arduino, sensors, wireless subsystem, and smartphone interface. The recorded feeding sequence was executed during a bench demonstration to transfer food toward the intended feeding position. This observation supports functional integration, but it does not establish independent feeding success across users or repeated trials. The monitoring subsystem is best regarded as an engineering feature; analogous embedded monitoring applications [12], [13] do not substitute for calibration or safety assessment of the present device.

4.2-Commanded Motion Analysis

MATLAB analysis shows commanded spans of 40° for Servo 1, 100° for Servo 2, 95° for Servo 3, and 180° for Servo 4. Servos 5 and 6 remain at 0° in the documented sequence. The largest discrete command changes occur near feeding and return transitions. Such discontinuities motivate future trajectory interpolation with explicit velocity and acceleration limits. However, without timestamps and measured joint responses, actual angular velocities, accelerations, tracking errors, and mechanical loads cannot be inferred. Closed-loop digital control methods such as those studied in [11] offer a possible future development direction.

4.3-Comparison with Recent Feeding-Robot Research

The present prototype should not be interpreted as outperforming autonomous feeding systems. Liu, F. et al. [1] provide voice-controlled food selection with a four-DOF arm; Mashrur et al. [2] use a six-DOF manipulator and depth cameras for more general feeding tasks; Choi et al. [3] add face recognition and food-acquisition estimation; and the Pick&Eat design in [4] integrates a wheelchair-mounted four-DOF arm with safety-oriented sensors. More recent portable systems emphasize user-in-the-loop adaptation and variable autonomy [5]. Against these systems, the contribution of the present work is lower-cost modular integration and a transparent command-level baseline, while its principal deficits are the absence of measured joint feedback, autonomous perception, quantitative safety metrics, and representative user trials.

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4.4-Study Limitations and Future Validation

The principal limitations are the lack of synchronized measured joint trajectories, repeated-trial statistics, calibrated sensor-error curves, collision-force measurements, feeding-cycle times, emergency-stop latency, and formal user testing. The prototype has not been validated for clinical or unsupervised use. Future work should implement joint feedback and bounded trajectory generation, then assess position error, repeated-cycle success, sensor calibration, physical contact forces, and usability under an approved participant protocol. Relevant digital PID and embedded monitoring studies [11-13] can inform system design, but their reported performance is not attributable to this prototype.

5-Conclusions

A low-cost assistive feeding prototype was implemented using Raspberry Pi and Arduino, six installed servo channels, environmental sensing, wireless monitoring, and smartphone interaction. The documented eight-step command sequence uses four varying servos, with respective commanded spans of 40°, 100°, 95°, and 180°; the remaining two channels stay at 0°. Functional bench operation and MATLAB command analysis establish a reproducible integration baseline, not quantitative tracking accuracy, repeatability, autonomous feeding, or clinical suitability. The next stage should collect synchronized commanded and measured joint angles, repeated-cycle times, calibrated sensor responses, contact-force and emergency-stop measurements, and user-centered outcomes. These measurements would enable rigorous evaluation of closed-loop control, safer trajectory planning, and eventual vision-guided feeding.

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