

Development of a suction mechanism with a suitable end-effector for robotic cotton picking

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In a robotic cotton picker, the picking arm has required a suitable end-effector to pick cotton bolls from the plant. Additionally, a suction mechanism has been required to transport the picked bolls into the storage tank. In the present study, a suction-based system has been developed in which the end-effector has removed the cotton bolls from the plant and a vacuum unit has carried them through a hose into the storage tank. Field tests have been carried out on non-defoliated cotton plants using three types of end-effectors, namely roller-type, chain-type, and tubular anthracite, at suction pressures of 25, 50, and 75 mmHg. The results have shown that the roller-type end-effector has achieved the minimum time required to suck a cotton boll (1.65 s boll^{-1}), the least cotton left in the boll (0.02 g boll^{-1}), and the highest picking efficiency (99.36%). The developed suction mechanism has efficiently picked cotton bolls from the plant when equipped with the roller-type end-effector at a suction pressure of 75 mmHg.

Keywords: Cotton boll, Roller-type, Suction pressure, Tubular anthracite, Vacuum unit

1 Introduction

Cotton is cultivated worldwide and holds significant importance for both the agricultural and textile industries. In India, cotton accounts for more than 60% of the fiber used in the textile industry¹. During 2022–23, the country's cotton output reached 341.91 lakh bales. As the largest cotton producer globally, India cultivates around 12.81 million hectares of this crop, making it a crucial commercial commodity². A harvesting robot usually has a vision system that helps to detection and location, and a manipulator to complete the picking task³. The end-effector is attached to the end of the arm to remove fruit (in this case, cotton seeds) from plants and place them in a storage tank⁴. Different designs of end-effectors use various methods for gripping and handling, such as soft fingers, scissors, rotating fingers, vacuum suction, etc⁵. The researchers developed an end-effector capable of harvesting seed cotton from plants with leaves. After testing different designs, they found that a belt-mounted, three-finger model was the most effective, collecting 66% to 85% of cotton per boll. The picking time varied from 4 seconds with a basic, less efficient design to 18 seconds with a more accurate and efficient system Gharakhani⁶.

Robotic cotton harvesters are not yet commercially available, and significant research on them has only emerged in recent years. Most of the studies that have been published focus on how the robot moves and finds cotton bolls Singh⁷. A Husky robot developed by Maja that had a suction end-effector with a fixed nozzle to pick up cotton bolls without any extra movement or adjustment⁸. Overall, most research teams developing robotic cotton harvesters have relied on vacuum-powered end-effectors. In a study, a mechanical cotton-picker fitted with a cyclone separator to boost blower speed achieved the highest picking efficiency of 96.3% when using a picker end diameter 25 mm at a 45 mmHg suction pressure Sharma⁹. A robotic cotton harvester developed by Fue that had a vacuum was attached to the rotating brush with gears end-effector that picked the cotton through a flexible plastic hose. In a simulated cotton field, the robot successfully picked 77.3 % cotton bolls, taking a time 17 s each cotton boll. In actual cotton field conditions, the success rate decreased to 75%, with each boll taking 38 seconds to pick from defoliated plants Fue¹⁰. The objective of this study was to design a suction mechanism for a robotic cotton picker capable of generating enough pressure to extract cotton bolls and transport them to the storage tank, as well as to identify a suitable end-effector for detaching the bolls from the plant.

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2 Materials and Methods

2.1 End-effector

The end-effector interacted with the cotton bolls to detach them from the plant. Three different type of end-effectors roller-type, chain-type, and tubular anthracite were tested for picking cotton bolls using the suction mechanism. Among these, the tubular anthracite design was selected for cotton boll picking. A CAD view of this end-effector is presented in Fig. 1.

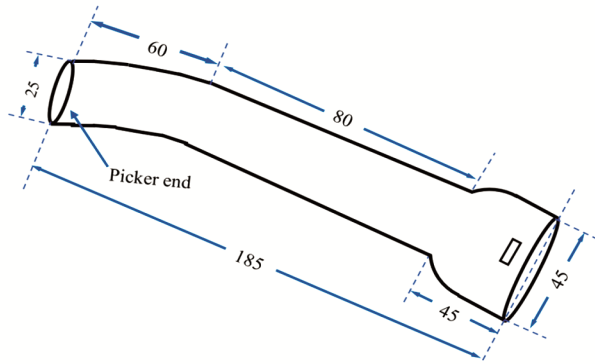


Fig. 1 — CAD view of the tubular anthracite end-effector (dimensions in mm).

It was a hollow cylindrical structure (185 mm long, 48 g) with a 25 mm picker end and a 45 mm hose-connecting end.

The chain-type end-effector having a DC motor, a continuous chain, and a pulley system. A CAD view of chain-type end-effector setup is illustrated in Fig. 2. A 12 V DC motor with a power output of 11 W was used to drive the mechanism, with an on/off switch positioned on the handle for control. The device weighed 860 g. The driven and driver pulleys measured 50 and 12 mm in diameter, respectively. The system featured two endless chains (each equipped with 44 prickles) attached to driven pulley. A motor shaft was transmitting power to the driver pulley and then transferred to driven pulley through a belt, resulting in the rotation of the endless chains.

These chains were equipped with prickles featuring small-edged teeth, designed to detach cotton bolls from the plant. The detached bolls entered the front of the device through a 50 mm-wide opening. A hose was attached beneath the end-effector for convey the collected cotton to a storage tank.

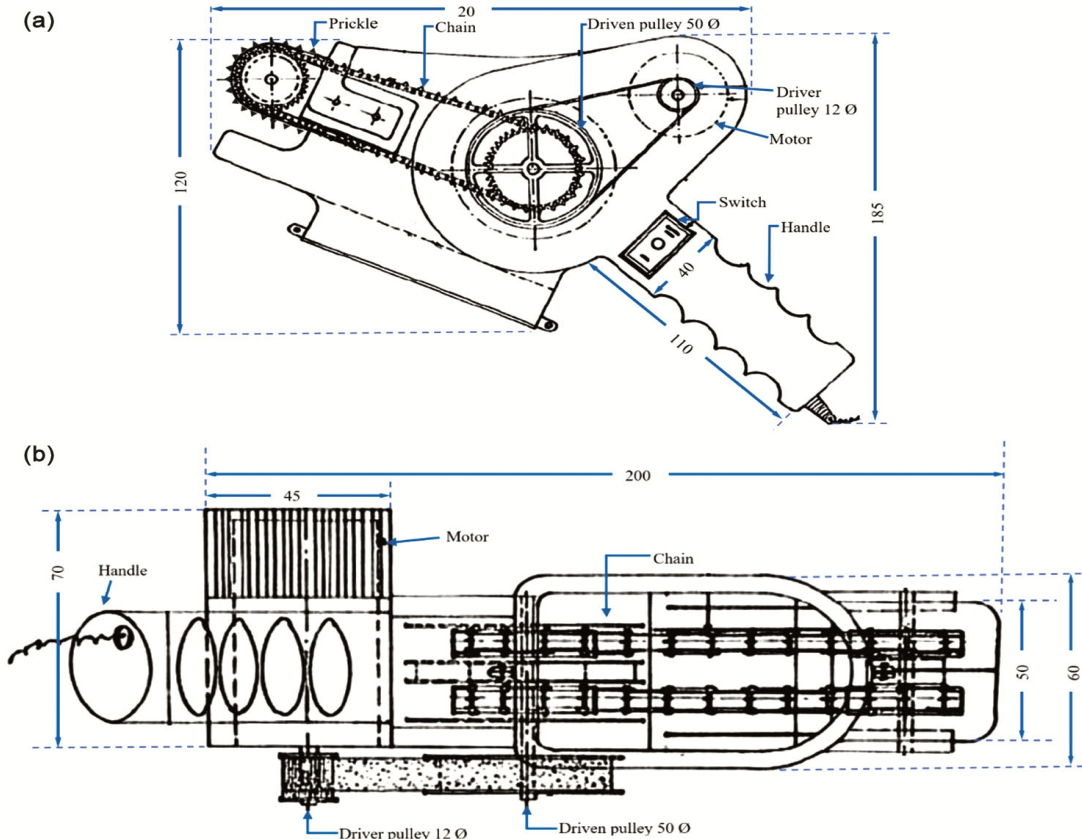


Fig. 2 — CAD view of the chain-type end-effector illustrating (a) the side view showing the prickles arrangement on the chain drive and (b) the top view depicting the attachment of two chains to the driven pulley; dimensions in mm.

The roller-type end-effector, weighing 810 g, featured a 12 V, 11 W DC motor, a belt–pulley system (12 mm driver, 10 mm driven), and a cylindrical roller of 50×30 mm was directly attached to the driven pulley, which rotated upon receiving power from the motor. The roller was equipped with 16 small prickle teeth designed to detach cotton bolls from the plant. A CAD view of the roller-type end-effector is illustrated in Fig. 3. The front opening of the roller-type end-effector, measuring 50 mm in width, allowed entry of

the detached cotton bolls. A hose pipe attached to the underside of the unit conveyed the collected cotton bolls to a storage tank. A comparison of the tubular anthracite, chain-type, and roller-type end-effectors is presented in Table 1.

2.2 Suction mechanism

A wet/dry type vacuum unit with a power rating of 1.5 kW was selected to generate sufficient suction pressure for extracting open cotton bolls from the

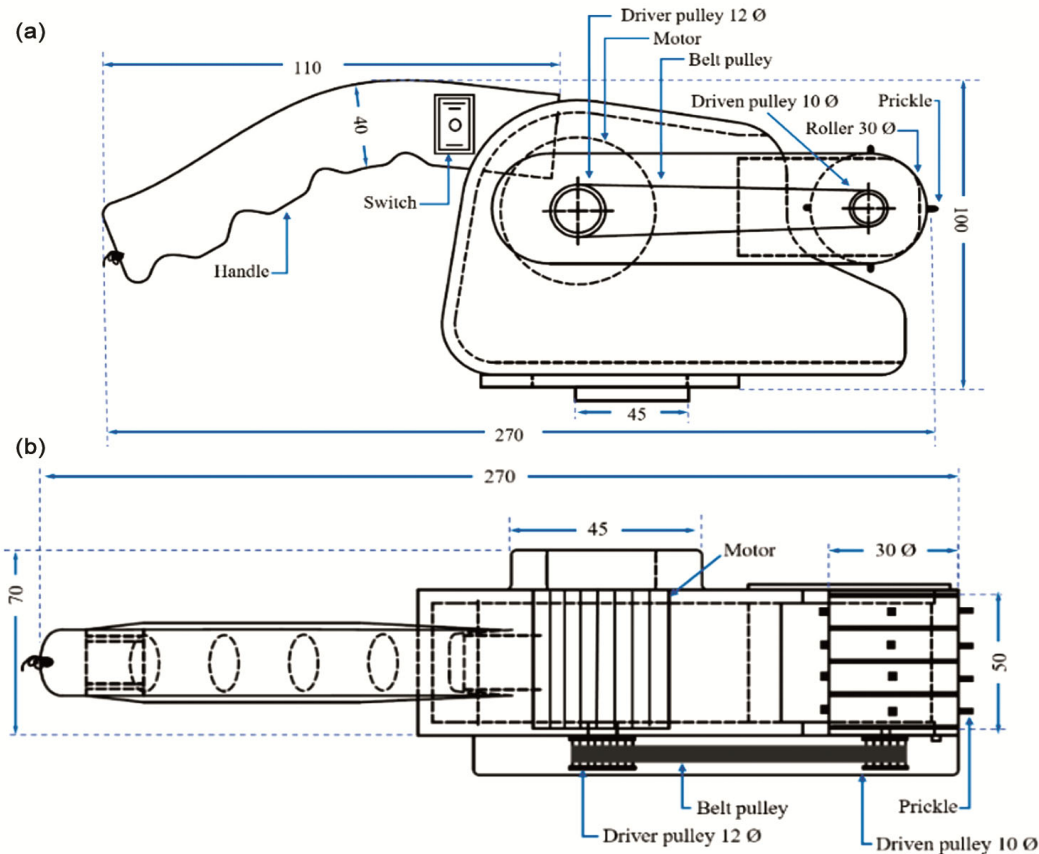


Fig. 3 — CAD view of the roller-type end-effector (dimensions in mm) illustrating (a) the side view showing the prickle arrangement on the roller and (b) the top view depicting the belt arrangement between the driver and driven pulleys for roller rotation.

Table 1— Comparison of tubular anthracite, chain-type, and roller-type end-effector.

Feature	Tubular Anthracite	ChainType	RollerType
Power and motor	-	12V DC motor, 11W	12V DC motor, 11W
Weight	48 g	860 g	810 g
End-Effector Shape	Hollow cylindrical tube	Chain-driven mechanism with pulleys and chains	Cylindrical roller mechanism with pulley and belt
Pulley Dimensions	-	Driver: 12 mm, Driven: 50 mm	Driver: 12 mm, Driven: 10 mm
Chains/Pulley Mechanism	-	Two endless chains, 44 prickles each, power transmitted via pulleys	16 prickles on cylindrical roller drum, power transmitted via pulleys
Roller or Chain Mechanism	-	Rotating chain mechanism with prickles to grip cotton bolls	Rotating cylindrical roller with prickles to grip cotton bolls
Cotton Boll Entry	Diameter at Picker End 25 mm	Front opening, 50 mm wide	Front opening, 50 mm wide

plant. This cylindrical vacuum unit measured 580 mm in height and 320 mm in diameter, operated on 220–240 V AC, and had a maximum airflow rate of 2.6 m³/min. An inverter converted 72 V DC supplied by six 12 V, 160 Ah lead-acid batteries connected in series into the required 220–240 V AC to run the vacuum unit, with an input charging voltage range of 180–265 V AC. A DC-to-DC converter supplied 12 V DC to the end-effector motor from the same 72 V DC battery setup. An infrared sensor (IR KY-032) mounted on the end-effector detected the presence of cotton bolls¹¹, triggering an Arduino Uno-controlled two-channel relay module that activated both the end-effector and the vacuum unit¹². Upon detection, end-effector detached the cotton from the boll, and the vacuum unit created suction through a 5000 mm hose pipe, transporting the boll into the vacuum unit's storage tank. The working principle of the suction mechanism is shown in Fig. 4.

The following code demonstrates the algorithm implemented on the Arduino Uno to control the activation of the end-effector and vacuum:

```
#define IR_SENSOR_PIN 2
#define RELAY1_PIN 3
#define RELAY2_PIN 4
void setup() {
  Serial.begin (9600);
  pinMode (IR_SENSOR_PIN, INPUT);
  pinMode (RELAY1_PIN, OUTPUT);
  pinMode (RELAY2_PIN, OUTPUT);
  digitalWrite (RELAY1_PIN, LOW);
  digitalWrite (RELAY2_PIN, LOW);
}
void loop() {
  // Read the IR sensor value
  int irState = digitalRead(IR_SENSOR_PIN);
```

```
  if (irState == HIGH) {
    Serial.println("Object detected! Activating End-
    Effector and Vacuum.");
    digitalWrite (RELAY1_PIN, HIGH);
    digitalWrite (RELAY2_PIN, HIGH);
    delay(5000);
    digitalWrite (RELAY1_PIN, LOW);
    digitalWrite (RELAY2_PIN, LOW);
    Serial.println("End-Effector and Vacuum turned
    off.");
    delay(2000);
  } else {
    digitalWrite (RELAY1_PIN, LOW);
    digitalWrite (RELAY2_PIN, LOW);
  }
}
```

2.3 Selection of end-effector

The Bt hybrid cotton¹³ variety RCH 846 BG II was selected for the testing. The experiment employed a vacuum unit, end-effectors, hose pipe, a stopwatch, and a weighing balance. The three end-effector types of roller-type, chain-type, and tubular anthracite were evaluated in field for picking cotton from non-defoliated plants at suction pressures of 25, 50, and 75 mmHg as shown in Fig. 5. In each trial, 50 cotton bolls were harvested, and data were collected on the time required to suck each boll, the amount of cotton remaining in the boll, and the overall picking efficiency. The picking was measured in seconds. Any cotton remaining in the boll after picking was weighed in grams per boll(g/boll). The weight of cotton picked (W_p) and the total boll weight (W_b), which included both picked cotton and leftover cotton, were noted. Picking efficiency was calculated as a percentage (%). The picking efficiency (η_e) was measured as:

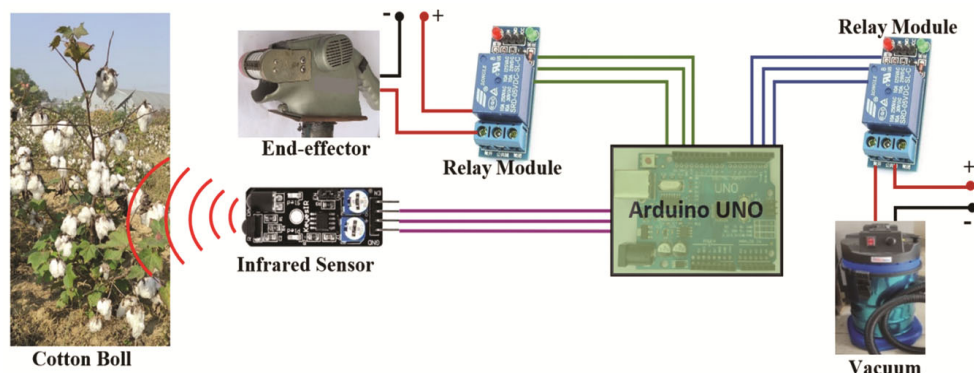


Fig. 4 — Working principle of the suction mechanism illustrating the infrared sensor interfaced with the Arduino for controlling end-effector and vacuum unit.

$$\eta_e = \frac{W_p}{W_{tb}} \times 100 \quad \dots (1)$$

3 Results and Discussion

3.1 Performance of suction mechanism along with different end-effectors in field

The efficiency of the suction mechanism was assessed in the field by testing three different type of end-effectors roller-type, chain-type, and tubular anthracite under suction pressures of 25, 50, and 75 mmHg. Data was analysed using a factorial completely randomized design in Statistix 10 software. Table 2 presents the interaction effects of end-effector type and a suction pressure on the time to suck boll, picking efficiency and the cotton left. Furthermore, Fig. 6 provides a graphical representation of these effects for the different suction pressures.

3.2 Effectiveness of the roller-type end-effector for a robotic cotton picker

A time required to pick a cotton boll using the three end-effectors tubular anthracite, chain-type, and roller-type under suction pressures of 25, 50, and 75 mmHg ranged from 1.65 to 8.21 s/boll (seconds per boll). The lowest picking time, 1.65 s/boll, was achieved with the roller-type end-effector at 75 mmHg. Thapa¹⁴ reported similar results, where a roller-type end-effector with a vacuum system picked

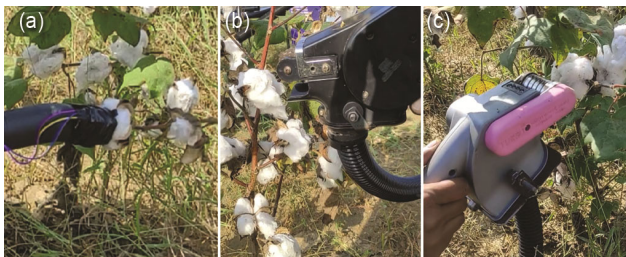


Fig. 5 — Cotton picking with end-effectors (a) tubular anthracite, (b) Chain-type and (c) Roller-type.

cotton bolls in about 2.5 s/boll in the lab and 3.0 s/boll in the field. The amount of cotton left in the boll after picking ranged from 0.02 to 0.34 g/boll (grams per boll). The least cotton left in the boll, 0.02 g/boll, was recorded with the roller-type end-effector at 75 mmHg. The picking efficiency ranged from 90.72% to 99.36%. The highest picking efficiency,

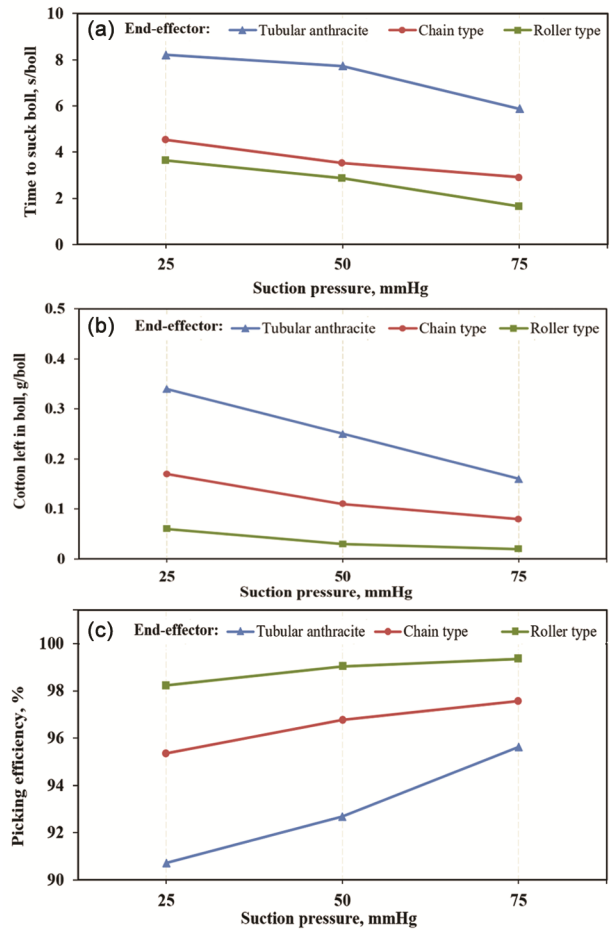


Fig. 6 — Impact of end-effector type and varying suction pressures on (a) time to suck cotton boll, (b) cotton left in boll and (c) picking efficiency.

Table 2— Comparison of time to suck boll, cotton left in boll, and picking efficiency across different end-effectors and suction pressures.

End-effector	Suction pressure (mmHg)	Time to suck boll (s/boll)	Cotton left in boll (g/boll)	Picking efficiency (%)
Tubular anthracite	25	8.21A	0.34A	90.72G
	50	7.72B	0.25B	92.69F
	75	5.88C	0.16C	95.63E
Chain type	25	4.54D	0.17C	95.35E
	50	3.52E	0.11D	96.76D
	75	2.91F	0.08DE	97.57CD
Roller type	25	3.64E	0.06EF	98.24BC
	50	2.88F	0.03F	99.04AB
	75	1.65G	0.02F	99.36A

Note: Mean values with different superscripts (A–G) differ significantly at $p < 0.05$, as determined by Tukey’s HSD test.

99.36%, was also achieved with the roller-type end-effector at 75 mmHg. Gharakhani⁶ conducted a related study and demonstrated that a three-finger moving pinned belt end-effector was capable of harvesting 66–85% of cotton bolls. According to Fue¹⁰, a 12 V DC motor-powered vacuum-assisted rotating brush roll end-effector attained a picking efficiency of 78.5%. Yadav¹⁵ conducted a related study in which a roller-type end-effector was integrated with a hydraulic arm developed for a robotic cotton picker, demonstrating a picking efficiency of 92.79%.

The analysis indicated that the roller-type end-effector, incorporating a rotating roller drum with prickles, performed better than the chain-type and tubular anthracite end-effectors by reducing picking time, minimizing residual cotton left in the boll, and improving overall picking efficiency. At a suction pressure of 75 mmHg, the system successfully conveyed cotton bolls through the hose without any blockage. For practical field application, integrating the roller-type end-effector with a robotic arm would enable fast and efficient cotton picking directly from the plants.

4 Conclusion

The studies were conducted on the performance of the suction mechanism that integrated with end-effector to harvest the cotton bolls. An experiment was conducted at three levels of end-effector (named tubular anthracite, chain-type, and roller-type) and three levels of suction pressure (25, 50, and 75 mmHg). After the investigation, selected a suitable end-effector based on their performance of time to suck boll, cotton left in the boll, and picking efficiency. The minimum time to suck was 1.65 s per boll observed at a suction pressure of 75 mmHg with a roller-type end-effector. The minimum cotton left in the boll was 0.02 g/boll observed for roller-type end-effector at suction pressure 75 mmHg. The maximum picking efficiency was 99.36 % achieved at a suction pressure of 75 mmHg with a roller-type end-effector. The most suitable combination of end-effector and suction pressure for achieving acceptable performance of suction mechanism to picking cotton bolls was a roller-type end-effector with a suction pressure

of 75 mmHg. To make this suction mechanism practically useful, the roller-type end-effector should be mounted on a robotic arm to enable rapid and efficient cotton picking directly from the plants.

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