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The Rise of Robots in China

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China is the world's largest user of industrial robots. In 2016, sales of industrial robots in China reached 87,000 units, accounting for around 30 percent of the global market. To put this number in perspective, robot sales in all of Europe and the Americas in 2016 reached 97,300 units (according to data from the International Federation of Robotics). Between 2005 and 2016, the operational stock of industrial robots in China increased at an annual average rate of 38 percent.

In this paper, we describe the adoption of robots by China's manufacturers using both aggregate industry-level and firm-level data, and we provide possible explanations from both the supply and demand sides for why robot use has risen so quickly in China. Our focus is on the manufacturing sector, which is responsible for over 80 percent of China's industrial robot use.

We begin by documenting the rising importance of China in the global robot market. We show that the industrial composition of robot adoption in China emphasizes the same industries as other major robot markets like Japan, the United States, South Korea, and Germany: automotive and electronics. Also, using

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administrative data from China, we examine signs of the sharp rise in production of robots in China, including some preliminary evidence from robot production and research firms and robotics-related innovation patents. We discuss how robot use in China's manufacturing sector is growing against the backdrop of two other factors: labor costs and government policies. The rise of robots in China coincides with the declining growth of the working-age population and rising wages. In this respect, the robot revolution in China reminds us of how high labor costs accompanied the Industrial Revolution in 18th-century Britain (as discussed in Allen 2009). At the same time, China's government has identified the robotics industry as a strategically important sector (along with artificial intelligence and automation), and has initiated various programs and subsidies to encourage the use of robots as a way of transforming and upgrading China's manufacturing industries.

Research on firm adoption of robots is often hindered by the lack of firm-level data. Several recent studies have investigated the link between robots and jobs using data aggregated at the country or industry level (for example, Graetz and Michaels 2018; Acemoglu and Restrepo 2017, 2018). The lack of firm-level information has often precluded more in-depth analysis (Seamans and Raj 2018). In fact, we have found no prior research on firms' robot adoption behaviors in any country. Thus, a key contribution of this paper is that we have collected some of the world's first data on firms' robot adoption behaviors with our China Employer-Employee Survey (CEES), which contains the first firm-level data that is representative of the entire Chinese manufacturing sector. After a brief introduction and overview of this data, we then discuss some of the firm-level patterns in robot adoption.

We find wide variations in China's adoption of industrial robots both across and within industries. We look at correlations between firms' decisions to adopt robot technology and a selection of variables: government connections that might encourage robot purchases; market factors that could influence robot adoption, such as labor costs, concern over product quality, and expanding production; and whether robot adoption is associated with firms in which the employees are more likely to be doing certain tasks. We find that several market and government factors are associated with robot adoption, and that firms requiring more manual tasks have a greater likelihood of robot adoption. We also investigate whether factors that influence a firm's robot adoption are different from those that influence a firm's general machinery usage. These findings suggest that it may be valuable for future research to study how different dimensions of labor costs and job task characteristics affect the use of robots versus general machinery.

Given the aggressive promotion of robot adoption and production via industrial policies, it seems that the Chinese government does not fear the consequences of this disruptive technology. Similarly, in our interviews with employers and employees, we do not find that they are nervous about job replacement. In light of these perhaps surprising findings, we offer a few possible explanations for why China embraces robots, from the perspectives of the government, the employers, and the workers.

Table 1
Annual Robot Sales in China and the World

Year	*World (1,000 units)*	*China (1,000 units)*	*China's share in the world (%)*
1995	69.3	0.0	0.0
2000	98.7	0.4	0.4
2005	120.1	4.5	3.7
2010	120.6	15.0	12.4
2011	166.0	22.6	13.6
2012	159.3	23.0	14.4
2013	178.1	36.6	20.5
2014	220.6	57.1	25.9
2015	253.7	68.6	27.0
2016	294.3	87.0	29.6

Source: International Federation of Robotics (2017).
Notes: This table shows the rise of China in the world robot market, especially after 2013.

Robot Adoption and Production in China

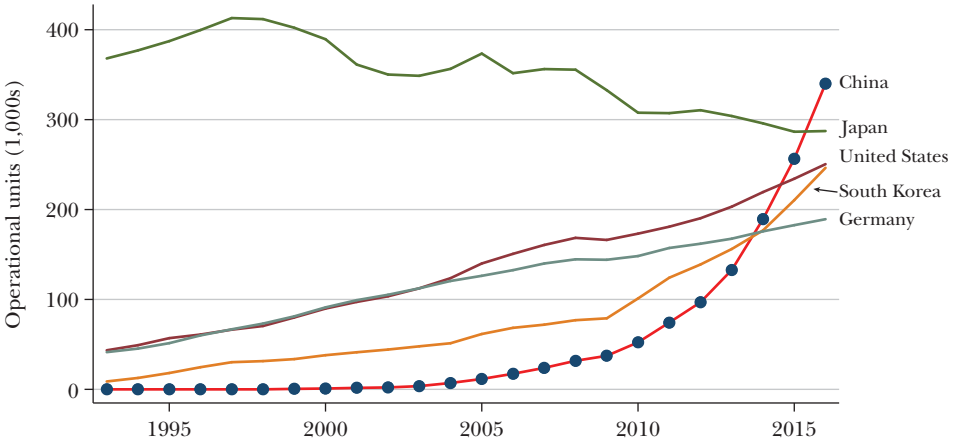
Robot Adoption

Annual sales of robots in China have risen dramatically (International Federation of Robotics 2017), as shown in Table 1. In 2000, a mere 380 units were sold in China, accounting for only 0.4 percent of the world total; China's share rose to 3.7 percent of annual global sales in 2005 and 12.4 percent in 2010. In 2016, sales further rose to 87,000 units, accounting for about 30 percent of the global market of 294,000 units.

Figure 1 shows the stock of operational robots for the top five robot markets in the world—China, Japan, the United States, South Korea, and Germany—which accounted for 72 percent of the world's operational robot units in 2016. China became the country with the largest operational robot stock in 2016, with 339,970 operational units—accounting for 19 percent of the total worldwide stock.

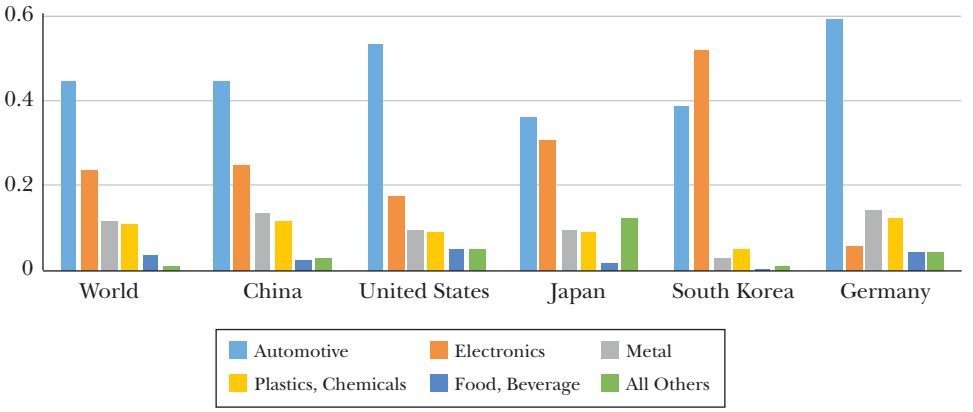
The distribution of robot usage across industries in China is similar to those of the other major markets for robots. In Figure 2, we plot the share of robots across industries in the manufacturing sector by major countries. Globally, the leaders in robot usage are the automotive and electronics industries (which accounted for 44.7 and 23.6 percent of all manufacturing robot usage in the world in 2015), followed by the metal (11.5 percent), plastic and chemical (10.8 percent), and food and beverage industries (3.7 percent). Textiles, wood and furniture, paper production, and glass and ceramics are among the industries in which robot adoption is still rare, and these industries are grouped in the "other" category, altogether accounting for only 1.3 percent of all manufacturing robots. There is some variation across countries. For instance, the share of robots used in South Korea for electronics and in Germany for auto production appears higher than in the other four countries. Nevertheless, China does not look systematically different in terms of industry-level robot adoption. In particular, the top industries in China for robot adoption are also automotive (accounting for 44.5 percent of

Figure 1
Stock of Operational Robots in Major Countries 2016



Source: Data is from International Federation of Robotics (2017).
Notes: This figure plots the operational stock of robots in the five major markets. China exceeded Japan and became the country with the largest operational robot stock in 2016.

Figure 2
Industrial Composition of Operational Robot Stock in Major Countries 2016



Source: Data is from International Federation of Robotics (2017).
Notes: This figure plots the share of robots across industries in the manufacturing sector by countries. China is not dramatically different from the other countries, suggesting that the supply of the technology matters in explaining which sectors use robots more.

all manufacturing robots), electronics (24.7 percent), metals (13.9 percent), plastics and chemicals (11.5 percent), and food and beverages (2.9 percent).

The higher rate of robot adoption in the automotive and electronics industries has implications for the future of robots in China. China has been the largest national producer of automobile units since 2008: indeed, since 2009, annual production of automobiles in China has exceeded that of the United States and Japan combined. China also clearly dominates the global electronics industry: over 70 percent of the world's computers and electronics are made in China. These industries in China seem likely to keep expanding, which implies that China will become an even more significant user of robots.

The variety of robots is also increasing in the Chinese market. Using data on 38 types of applications from the International Federation of Robotics, we construct a Herfindahl–Hirschman index to capture the variety of robots by their applications.[1] For the entire world, this index remained relatively stable at the level of 0.10 to 0.11 between 2005 and 2015. In contrast, the index for China decreased from 0.16 in 2005 to 0.10 in 2015, implying that applications of robots broadened within a decade. In 2005, the top four applications (handling operations and machine tending, plastic molding, welding and soldering, and arc welding) accounted for 75 percent of the market; in 2015, the share of the top applications (handling operations and machine tending, welding and soldering, spot welding, and fixing and press fitting) dropped to 54 percent of the market. Once again, this change shows that the variety of robots in China has increased.

Robot Production and Innovation by Firms

The rise of robot production in China is no less striking than that of robot adoption, although this increase is more recent. In 2012, only about 5,800 robots were produced in China (based on our reading of various government reports). By 2017, however, the number of robots produced in China annually had risen more than 20-fold to 131,000, among which 29 percent (37,800 units) were made by local (nonforeign) firms.

Unsurprisingly, the number of firms that produce robots, or do robotics research, has been rising fast. To our knowledge, little has been written on China's robot manufacturers and their technology. As a starting point, we examine the number of firms with "robotics" in their names by year, using firm registration data provided by the State Administration for Industry and Commerce (SAIC). In 2005, China only had 221 registered robotics firms, but by the end of 2015, the number had risen to 6,478. The year 2013 appears to have been a turning point for robotics manufacturers: the number of registered firms doubled each year during 2013–2015. It is unclear how profitable these firms are: after all, most of them are newly established. But based on public reports, government subsidies are a major driver of the rise of these manufacturers. In 2016, 40 percent of the net profits of the four publicly listed robotics firms—SIASUN Robot & Automation, Estun

[1] We calculate the Herfindahl–Hirschman index by squaring the market share of each application and then summing the resulting numbers.

Automation, Guangdong Topstar Tech, and Shanghai Step Electric Corporation—derived from government subsidies (as reported by Lin 2018).

China is also advancing rapidly in robotic technology. As a first effort of gauging China's progress in robot production technology, we examine innovation patents with "robotics" in their titles granted by China's State Intellectual Property Office (SIPO). In 2000, SIPO granted only 54 innovation patents with "robotics" in their titles, but the number rose to 319 in 2010 and 1,145 in 2015. The annual growth of the number of robotics-related innovation patents was around 40 percent during 2005–2015.

Labor Force and Government Subsidy

Although China's original success as the "world's factory" was built upon the cheap labor of hundreds of millions of manufacturing workers, China has now been experiencing the combination of a shrinking labor force and rapidly rising labor costs over the last decade (as discussed in this journal by Li, Li, Wu, and Xiong 2012). In turn, this has led to an increase in both economic pressure and political support for growth of the Chinese robotics industry.

China's past economic growth was in part driven by a "demographic dividend"—a rise in the working-age population as a share of China's total population. However, China is rapidly approaching a demographic deficit. China's working-age population (age 15–64) is declining both in absolute size and as a share of China's overall population. The annual increase in China's working-age population peaked in 2003 at around 17.7 million, but it then started declining and turned negative in 2015. Interestingly, the timing for the rise of robots roughly corresponds to that for the declining labor force; that is, the rise of robots started in 2003, when the gains in the working-age population started to decline, and accelerated since 2010, rising even faster since 2015, when the size of the working-age population declined outright.

During 2005–2016, the importance of manufacturing employment has been gradually increasing. In 2005, among the 746 million individuals in the labor force, 62 million (8.3 percent) were employed by the manufacturing sector; in 2016, among the 776 million workers in the labor force, 103 million (13.3 percent) were employed by the manufacturing sector. An important factor underlying this increase is that rural workers have moved to the manufacturing sector in urban areas.

Besides the size of the labor force, the skill composition of the labor force is also changing, especially due to the large-scale expansion of college enrollments from 1999 to 2009, which increased the number of college students by an average of 18 percent each year (Li, Loyalka, Rozelle, and Wu 2017). In 2005, only 6.6 percent of the labor force and 7.6 percent of manufacturing workers had a college education. These numbers rose to 18.1 percent for the whole labor force and 15.8 percent for manufacturing workers in 2016. Although it is impressive to see that the college education share doubled for the manufacturing sector within a decade, this change is actually smaller than that for the whole labor force, likely reflecting the difficulties that China's manufacturers have in attracting workers with college education.

Accompanied by the change in labor force, the wages of urban workers are also rising. During 2005–2016, China's average annual growth rate in real wage was 10 percent (deflated by China GDP deflator) for those employed by urban units,

and the annual wage growth rate for the manufacturing sector was 9.7 percent. Manufacturing labor costs per hour in China were estimated to be $3.30 (in US dollars) in 2015, which is higher than those in Malaysia, India, Thailand, Indonesia, and Vietnam (Giffi, Rodriguez, Gangual, Roth, and Hanley 2016). Thus, to deal with the challenges of a labor shortage and rising labor costs, China's manufacturers have experienced pressures to automate, use machinery, and adopt robots.

In addition, the Chinese government has aggressively promoted the production and use of industrial robots in recent years. In 2013, for example, the Ministry of Industry and Information Technology (MIIT) released its "Guidance on the Promotion and Development of the Robot Industry." Some goals outlined in the report included developing 3–5 world-leading robot companies and 8–10 supporting industrial clusters; increasing China's global market share of high-end robot products to more than 45 percent; and promoting the use of robots in factories with the aim of a density of 100 robots per 10,000 workers. These initiatives were further bolstered by the launch of the "Made in China 2025" program in the year 2015, which set national goals of producing 100,000 industrial robots per year and achieving a density of 150 robots per 10,000 workers by 2020, which would triple the robot density in the manufacturing sector reported for 2015 (State Council 2015). In addition, in 2016, the MIIT, the National Development and Reform Commission (NDRC), and the Minister of Finance jointly launched the Robotics Industry Development Plan (2016–2020) to promote robot applications to a wider range of fields including the service sector. This plan sets several targets by 2020, including 100,000 industrial robots annually produced by domestic technology and annual sales of ¥30 billion (about $4.4 billion in US dollars) for service robots.

Like Chinese industrial policies implemented in other areas (for example, the electric car and solar industries), the most common form of government support is subsidies, which appear to be effective (but not necessarily efficient) at steering firms into industries they might otherwise ignore.[2] To the best of our knowledge, no systematic data exist on subsidies from the Chinese government to finance the production and use of industrial robots, but numerous media reports have commented on the scale and size of these subsidies. At the local level, governments have set up some investment capital and allocated funds to support robot usage and innovation. Like any other type of policy in China, there is regional variation in policies supporting the adoption of robot technology related to factors like differences in fiscal capacity, regional industrial structure, and priorities of local leaders. As one example, in 2015 the government of Guangdong Province put together a fund of $150 billion (in US dollars) to encourage firms to invest in automation technology and promote robotics innovation (Yang 2017).

Contrasting with the negative sentiment about robots in many countries due to their potential to replace jobs, the overall perception of robots in China has always been positive. The threat of job replacement is rarely mentioned in the government documents promoting robot adoption and production. Instead of

[2]As usual, political economy is likely to matter. Providing subsidies creates more opportunities for rent-seeking than alternatives like providing training.

worrying about job replacement, the government emphasizes robot adoption as a way to deal with challenges in the labor force. One reason that Chinese see robotics (and automation) as a positive phenomenon is that advances in science and technology are believed by many to be essential for China's rise as a world power. This perception partly originates from China's painful early encounters with Western powers. Since the Opium War in the 1840s, China has endured numerous foreign invasions, which many have attributed to the inferiority of technology in China. The following discussion of the importance of technology in a 2016 national plan by the State Council is revealing:

> One important reason why China fell into backwardness and took beatings in the modern era is that the previous industrial revolutions slipped through our fingers, leaving us with weak technology and a weak state. To realize the great rejuvenation of the Chinese nationhood that is the Chinese Dream, we must make genuine use of science and technology, this revolutionary force and lever of power in the highest sense.

During the decade between January 2009 and January 2019, *People's Daily*—the flagship newspaper of the central government—published 346 reports related to industrial robots. In these reports, "industrial/technological/robot revolution" was mentioned 206 times, and "job replacement/unemployment" was mentioned 85 times. When examining the reports mentioning job replacement, we find that the sentiment is still generally positive. Below is an example from that paper (He 2016, translated from Chinese), which illustrates the reasoning of government officials:

> Since 2014, Dongguan City (a city in Guangdong Province) has implemented the "replacement of workers with robots" incentive (funding) policy to promote the transformation and upgrading of the manufacturing industry. As of the end of last year, the number of enterprises applying for these funds reached 1,262, with a total investment of over 10 billion yuan and a reduction of 71,000 jobs. But the practice has proved that it is a big misunderstanding that the robots will steal people's jobs and cause unemployment. He Yu, deputy mayor of Dongguan City, said that the city has made a serious analysis of employment. More than 75 percent of the enterprises that implement "replacement of workers with robots" either have not changed or have increased the number of workers. Like Zheng Zhangteng (a Chinese worker), affected by the "replacement of workers with robots" policy, a large number of front-line operators are liberated from the heavy and dirty working environment. After training, they are transferred to technical personnel positions, and they have upgraded their careers while upgrading their industries. Even if there were a small number of people who left their positions, they were immediately absorbed by other companies.

Given this background, China seems likely to lead the world in the volume and sales of robot adoption and production in the future. Current robot technology is

most suitable in auto and electronics industries, and since China dominates global sales in both areas, more and more robots will be used in China. With China's declining labor force and rising wages, more of China's manufacturers will find it profitable to adopt robots. Furthermore, government industrial policies can induce additional demand. In the next sections, we employ micro-level data to further examine the patterns of robot adoption at the firm level.

The China Employer-Employee Survey

The China Employer-Employee Survey (CEES) is a new longitudinal study of manufacturing firms and workers in China. CEES was initiated by two of the authors (Hong Cheng and Hongbin Li) together with Yang Du at the Chinese Academy of Social Sciences and Albert Park at the Hong Kong University of Science and Technology. The survey is administered by the China Enterprise Survey and Data Center at Wuhan University, which is directed by Cheng and Li. It began in 2015 with a survey of firms and workers in the coastal province of Guangdong, which borders Hong Kong, and expanded to the interior province of Hubei in 2016. Guangdong has been China's most important industrial province in the past few decades and accounted for 13.4 percent of all manufacturing firms and 19.4 percent of all manufacturing workers in China in 2015. In 1980, when the central government initiated the Special Economic Zones policy, three of the four Special Economic Zones were located in Guangdong. In recent years, the manufacturing sector has been expanding to the interior provinces like Hubei. In 2015, Hubei accounted for 4 percent of all manufacturing firms and 6.6 percent of all manufacturing workers.

In this paper, we focus on the 2016 data (covering information on firm behavior in 2015), in which we began to include questions on robots in the survey instrument. For the most recent round of the survey, conducted in the summer of 2018, we followed up with the previously surveyed firms in Guangdong and Hubei and expanded the survey to include three additional provinces: Jiangsu, Liaoning, and Sichuan. This data is in the process of being entered and cleaned. We plan to make the CEES data available to researchers step by step. The existing data has also been used to study the performance of state-owned enterprises (Cheng, Li, and Li forthcoming) and management practice (Bloom, Cheng, Duggan, Li, and Qian 2018), where the authors provide a detailed description of other variables in the data.

Sampling

In 2016, the China Employer-Employee Survey was conducted in Guangdong and Hubei. We used the third National Economic Census, which was conducted in early 2014, as our sampling frame. Sampling was conducted in two stages, each using probability proportionate-to-size sampling, with size defined as manufacturing employment. In the first stage, 20 county-level districts were randomly sampled in each province, with probabilities proportionate to manufacturing employment in each district. In the second stage, 50 firms were sampled in each district as a target sample, again with probabilities proportionate to manufacturing employment in

each firm. Enumerators then visited the 50 firms and attempted to survey the first 36 eligible firms (that have production activities in the sampled district). With this approach, the firm sample can be viewed as reasonably representative of manufacturing firms in China.

Employees were also randomly selected using stratification. We first asked each firm to provide a list of all employees enrolled at the end of the previous year, with middle and high-level managers listed separately. Then, we randomly selected ten employees in each firm (six to nine for smaller firms), three (two for smaller firms) of whom were middle and senior managers. If selected employees could not participate (for example, because they were not working on-site during the survey period), they were replaced with the closest name on the list of workers. This process continued until the targeted number of sampled employees was reached.

After excluding firms that were no longer in operation, there were 1,326 firms across 26 prefectures in Guangdong and Hubei that were eligible to be surveyed. In 2016, we managed to survey 1,115 firms and achieved a response rate of 84 percent. The median asset value of surveyed firms was ¥55.7 million (roughly $9 million in US dollars). The median number of workers across these firms was 160, with a 25th percentile of 55 employees and a 75th percentile of 520. About 90 percent of the initially sampled workers participated in the employee surveys. This provides us with information on 8,848 workers, among which 3,691 are production-line workers.

Robot Adoption across Industry and Region

We asked two sets of questions on robot adoption in the survey. First, we asked whether a firm utilized robots in its production processes in 2015. According to our data, 8.6 percent of the 1,115 firms used robots in 2015. Second, we asked questions related to the purchase of robots, namely, how much robots cost, and whether the government had subsidized the firm's purchase.

The responses reveal considerable variation in the adoption of robot technology across industries. Indeed, the share of robot units across industries in the International Federation of Robotics data versus the probability of using robots by industries in our CEES data have a correlation coefficient of 0.97, which provides a useful validity check of the quality of CEES data.[3] Such differences across industries also lead to differences in the use of robots by Chinese firms across regions. For example, we find that in Guangdong's Huizhou prefecture, where electronics manufacturing is the dominant industry, over 20 percent of sampled firms use robots. In contrast, no sampled firms in Hubei's Qianjiang prefecture use robots, likely because firms in this prefecture are generally involved in the garment and leather product industries where robot adoption is still rare.

However, our results also show substantial variation in robot usage across firms within a given industry. Indeed, we find that province-by-industry fixed effects

[3]This correlation is visualized in an online Appendix available with this paper at the journal website, where we also present more background information about the China Employer-Employee Survey, including summary statistics of the data for 2015.

(where "industry" refers to the 12 industries defined by the International Federation of Robotics) can only explain 9 percent of the variation in firm-level robot adoption. Therefore, it appears useful to investigate firm-level correlates of robot adoption.

Patterns in the Adoption of Robots by Chinese Firms

In this section, we use a series of regressions to describe the patterns of robot adoption by Chinese firms. This evidence is primarily cross-sectional and descriptive. However, we believe it nonetheless sheds light on the rise of robots in China.

As a starting point, we have already noted that firms in the automotive and electronics sectors are more likely to use robots. Moreover, firm size and capital-labor ratio are also correlated with a greater probability of robot adoption. As shown by the binned scatter plots in Figure 3A, an increase in log number of workers (x-axis) by one standard deviation is associated with the rise in the probability of robot adoption (y-axis) by 8.3 percentage points, after controlling for province and industrial fixed effects. Similarly, Figure 3B shows that an increase in log capital-labor ratio by one standard deviation is associated with the rise in the probability of robot adoption by 3.7 percentage points. These correlations still hold when we run a horse race test between firm size and capital-labor ratio, suggesting that both factors are relevant.

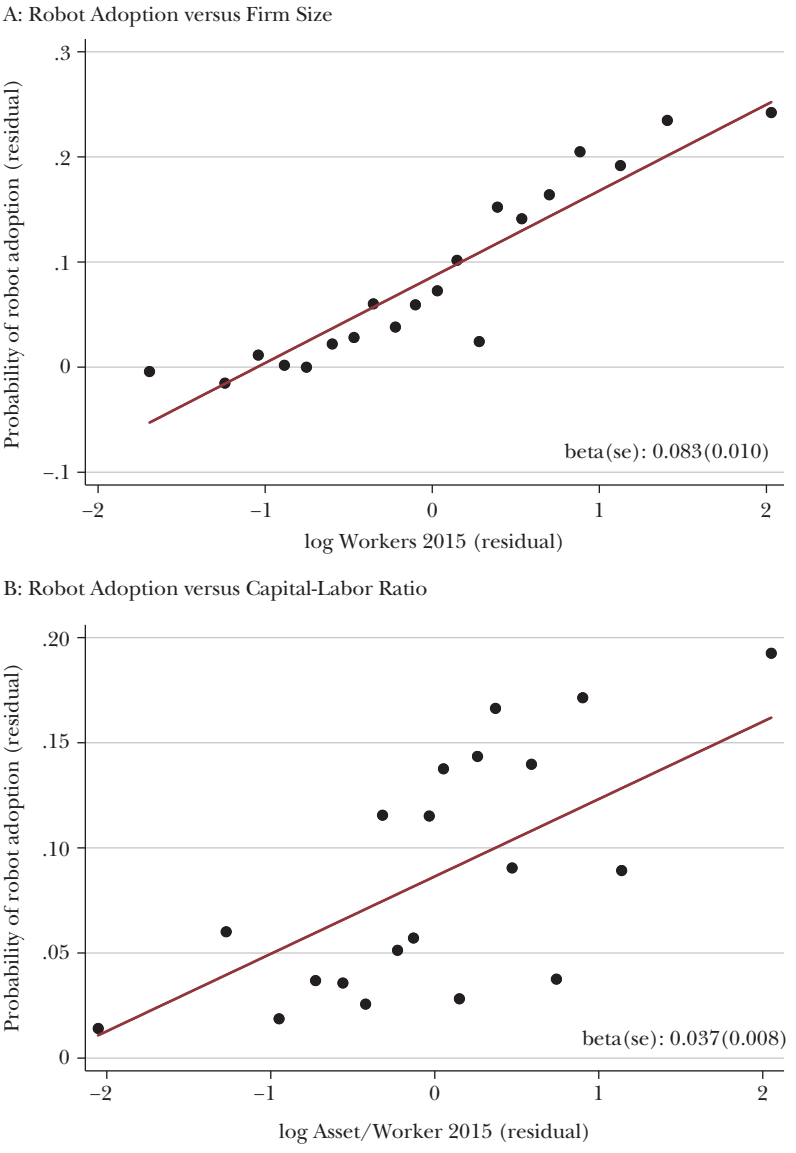
Next, we examine patterns in firms' robot adoption that reflect factors other than industry, firm size, and running a capital-intensive plant. In particular, in Table 2, we summarize the correlations between robot adoption and factors we care about in regressions that control for province and industry fixed effects, log number of workers, and log capital-labor ratio. In essence, we are comparing firms with similar size and capital-labor ratio within the same industry and province. We look at 12 different factors, some involving government, some involving market factors, and some involving the mix of tasks at the firm. The coefficient in each cell of Table 2 is generated by a separate regression.

Government Policy

One possibility is that China's firms adopt robots because of government policies that facilitate or subsidize robot purchases. In the survey, we asked whether firms receive subsidies specific to robot adoption. Among all robot-using firms, 15 percent answered "yes," suggesting that government industrial policies may have contributed to their adoption decisions.

It is also important to consider whether politically connected firms might be more likely to adopt robots either because of their better access to government funding or because of their tendency to comply with government policies. To examine the potential influence of political connections on firms' robot adoption behavior, we first examine the impact of firm ownership. In our sample, 12 percent of firms are state-owned enterprises (which include those with collective ownership). The coefficient reported in cell 1 of Table 2 does not suggest that state-owned enterprises are more likely to adopt robots than other firms. If anything, they are

Figure 3
Robot Adoption: Firm Size and Capital-Labor Ratio



Source: Authors.
Notes: This figure plots the correlations between firm size, capital-labor ratio and robot adoption, after controlling for province fixed effects and industry fixed effects. Log workers and log capital-labor ratio are standardized so that 1 (and –1) means one standard deviation above (and below) average. Each dot indicates a bin of firm observations. These correlations also hold when we run a horse race between these two factors.

Table 2

The Correlation between Robot Adoption and Firm Characteristics

(Dependent Variable: Robot Adoption = 1 if yes, 0 if no)

	(1)	*(2)*	*(3)*	*(4)*	*(5)*	*(6)*
	SOE	*CEO: Party member*	*ln (Wage cost) std*	*Union*	*ln (Workers leaving voluntarily) std*	*Quality control*
coefficient	–0.042	0.024	0.031	–0.020	0.027	0.006
s.e.	(0.025)	(0.018)	(0.014)	(0.017)	(0.013)	(0.011)

	(7)	*(8)*	*(9)*	*(10)*	*(11)*	*(12)*
	Defect rate std	*Exporter*	*ln (Sales change) std*	*Manual task std*	*Routine task std*	*Abstract task std*
coefficient	0.003	0.023	0.011	0.015	0.006	-0.005
s.e.	(0.009)	(0.019)	(0.006)	(0.007)	(0.007)	(0.008)

Notes: This table summarizes the correlations between each factor and robot adoption, after controlling for province fixed effects, industry fixed effects, log number of workers, and log capital-labor ratio. The factors are: being a state-owned enterprise (1); the chief executive officer (CEO) is a member of the Communist Party (2); a one-standard-deviation increase in log wage (per worker) (3); labor union presence (4); a one-standard-deviation increase in the log of workers leaving voluntarily (5); having quality control (6); a one-standard-deviation in the increase of defect rate (7); being an exporter (8); a one-standard-deviation increase in sales growth (9); a one-standard-deviation increase in manual task (10); a one-standard-deviation increase in routine task (11); and a one-standard-deviation increase in abstract task (12). The coefficient in each of the 12 cells is generated by one independent regression. Robust standard errors are reported in the parentheses.

less likely to do so, as we find a negative correlation between robot adoption and being a state-owned enterprise. One possible reason is that they may be less responsive to market forces, which, we will show in the next section, are strongly correlated with robot adoption.

In addition, 35 percent of the firms in our sample have a chief executive officer (CEO) who is a member of the Communist Party—another indicator of political connectedness. This factor is positively correlated with robot adoption, as shown in cell 2 of Table 2. The correlation coefficient is not precisely estimated, but the magnitude is sizable: the CEO's party membership is associated with a 2.4 percentage point higher probability of robot adoption. This result becomes stronger after controlling for the CEO's gender, age, and education (not shown here). These results suggest that government policies and political factors should be considered when examining the robot adoption behaviors of Chinese manufacturing firms.

Market Factors: Labor Cost and Others

We now examine this question: To what extent is the adopotion of robots by Chinese firms correlated with market factors, such as the ability to decrease labor costs, improve product quality, and expand production?

Rising labor cost is often cited as a main motivation for robot adoption in China (for example, Bland 2016). We test this conjecture by using three measures of firm

labor costs: the total wage bill (in logs) of a firm, whether a firm has a labor union, and the worker turnover rate. Because we control for firm size, the wage cost variable can be viewed as reflecting the average wage cost of a firm.

The wage bill is positively correlated with robot adoption, as shown in cell 3 of Table 2. Specifically, a one-standard-deviation increase in log wage (per worker) is associated with an increase in the probability of robot adoption by 3 percentage points (relative to the mean of 9 percent). While 60 percent of the firms have labor unions, we find no positive correlation between labor union presence and robot adoption (see cell 4 of Table 2), a result consistent with the understanding that labor unions in China lack independence and do not play a critical role in wage bargaining. The lack of strong and independent unions in China may also partly contribute to workers' tolerance of robot adoption.

We also examine how labor turnover affects robot use. Our data shows that voluntary turnover is much more common (with a mean of 0.31 of the annual workforce) than involuntary turnover (with a mean of 0.13). The data on "voluntary" and "involuntary" turnover is based on responses from those who answered the firm-level survey (that is, the managers and their team members). In our worker survey answered by the employees, we also find that voluntary turnover is more common than involuntary turnover. For instance, when being asked why they left their previous jobs, 61 percent of the workers answered that they left voluntarily because they got a better job or wanted to search for a better job, and another 21 percent left voluntarily for other reasons (like returning to their hometown or family matters). Regarding involuntary turnover, 14 percent answered that they left because their firms went out of production or got restructured, while 2 percent cited downsizing payrolls.

Voluntary worker turnover is positively correlated with robot adoption, while involuntary turnover is not. As shown in cell 5 of Table 2, an increase in log *voluntary turnover* by one standard deviation is associated with an increase of 2.7 percentage points in the probability of robot adoption. In contrast (but not shown on the table), there is no significant correlation between robot adoption and *involuntary turnover* (with a coefficient of -0.003 and standard error of 0.011). Because involuntary turnover is more likely to be the consequence of robot adoption while voluntary turnover is more likely to be the cause of robot adoption, these patterns suggest that few workers have been displaced as a result of robot adoption.

We also examine other market factors, such as quality control and production growth, on the likelihood of robot adoption. Firms may adopt robots to meet high quality standards. To examine the role of quality control, we consider whether a firm has a quality control strategy in place, the defect rate of products, and whether a firm is involved in exporting (assuming exported products are of higher quality). We also examine whether a firm is expanding production, as it is likely that high-growth firms may find it difficult to recruit a sufficient number of workers. For this reason, they may be more likely to employ robots than other firms. We use the growth of sales revenue over the past year as a measure of production growth.

As shown in cells 6 and 7 of Table 2, we find no evidence suggesting quality control is correlated with firms' robot adoption behavior, while in cells 8 and 9 we

find weak evidence for the correlation between production growth and robot adoption. Of course, our variables do not perfectly measure either quality control or production growth, and we are looking at cross-section data for a single year rather than time-series data. We plan to revisit these hypotheses after we collect more data in future years.

Job Tasks

We next examine the extent to which job tasks are associated with firm adoption of robots, as certain tasks might be more suitable for industrial robots to complete than others. We assess tasks at a given firm using information collected at the worker level. Following the approach of Autor, Levy, and Murnane (2003), we asked detailed questions in the survey related to the task characteristics of each sampled worker. In our analysis, we employ a principal component analysis method to measure the degree to which the job/post of a worker requires a manual, routine, or abstract task. For each worker's job, we assign a value of 1 if it requires that type of task, and 0 otherwise. We then calculate the firm-level aggregated task measures by taking the average of worker-level task measures.[4]

Linking robot adoptions to these firm-level task measures, we find that robots are more prevalent at firms where employees are commonly doing manual tasks, but not those that require routine or abstract tasks. As can be seen in cell 10 of Table 2, the correlation between robot adoption and our manual task measure is positive and significant. In terms of the magnitude, an increase in the manual task measure by one standard deviation is associated with a 1.5 percentage point increase in the probability of robot adoption. In contrast, the correlations between routine/abstract tasks and robot adoption are small in magnitude and not significantly different from zero, as shown in cells 11 and 12. Although some may assume that robots were likely to replace routine tasks a priori, our data do not support this conjecture. One possible reason is that robots have taken on the manual, dirty and health-hazardous tasks, but at least so far have not been able to replace more delicate routine tasks in a cost-effective manner. In addition, because it is difficult for manual workers to express themselves in Chinese society, their voice on robot adoption is unlikely to be heard.

Results are similar when we include all 12 of these factors in the regressions, as shown in Table 3. In column 1 of Table 3, we report a regression with the same dependent variable (a zero-or-one variable indicating the adoption of robots), including all the firm characteristics together as independent variables. The patterns are similar to those we find in Table 2. In the second column of Table 3, we use the (log of) value of robots as an outcome variable and also obtain qualitatively similar results.

[4]These aggregate task measures are correlated as one might expect. The manual task measure is positively associated with the routine task measure, with a correlation coefficient of 0.33. The manual task measure is also negatively correlated with the abstract task measure, with a correlation coefficient of -0.22. For details of summary statistics see the online Appendix available with this paper at the journal website.

Table 3
Firm Characteristic, Robot Adoption, and General Machinery Usage

	Dependent Variable			
	(1) *Robot Use (0/1)*	*(2)* *ln (Robot Value)*	*(3)* *ln (Machine Value)*	*(4)* *(3) – (2)*
ln (Workers) std	0.039	0.341	1.308	–0.967
	(0.020)	(0.139)	(0.105)	(0.174)
ln (Asset/Worker) std	0.022	0.167	0.607	–0.440
	(0.009)	(0.062)	(0.063)	(0.077)
SOE	–0.023	–0.323	0.034	–0.358
	(0.027)	(0.168)	(0.167)	(0.234)
CEO: Party member	0.048	0.291	0.046	0.245
	(0.020)	(0.123)	(0.104)	(0.153)
ln (Wage cost) std	0.023	0.071	0.332	–0.261
	(0.015)	(0.111)	(0.091)	(0.142)
Union	–0.023	–0.140	0.204	–0.344
	(0.019)	(0.112)	(0.106)	(0.150)
ln (Workers leaving voluntarily) std	0.027	0.085	–0.007	0.092
	(0.013)	(0.078)	(0.064)	(0.095)
Quality control	0.003	–0.009	0.062	–0.071
	(0.012)	(0.073)	(0.106)	(0.123)
Defect rate std	0.000	0.002	–0.041	0.044
	(0.010)	(0.056)	(0.031)	(0.056)
Exporter	0.033	0.209	–0.153	0.362
	(0.020)	(0.132)	(0.108)	(0.160)
ln (Sales change)	0.011	0.061	–0.040	0.102
	(0.006)	(0.038)	(0.043)	(0.063)
Manual task std	0.013	0.093	–0.013	0.105
	(0.008)	(0.051)	(0.051)	(0.070)
Routine task std	0.000	–0.035	0.072	–0.106
	(0.008)	(0.050)	(0.052)	(0.070)
Abstract task std	0.002	0.023	0.154	–0.131
	(0.009)	(0.068)	(0.051)	(0.083)
Province, industry fixed effects	Y	Y	Y	Y
Observations	911	911	911	911
R_2	0.194	0.157	0.650	0.309

Notes: This table compares robot usage with general machinery usage. We find that the factors driving machinery usage are not the same as those driving robot adoptions. Besides log workers and log capital-labor ratio, the other variables are the same as those in Table 2. Column 4 tests the significance of these differences. Robust standard errors are reported in the parentheses.

Robots versus Other Machines

Next, do the factors correlated with the robot adoption behavior of firms differ from those that are correlated with the general use of machinery? To compare the correlations of different factors with the uses of machinery versus those with robot adoptions, we estimate a regression with the (log of) the value of machinery as the outcome variable and report it in column 3 of Table 3. We also report in column 4 the significance of the difference between robot adoption and machinery use.

There are indeed differences in the correlations between robot and machinery usage. First, although robot adoption is positively associated with firm size and the capital-labor ratio, the correlations are much smaller than those for general machinery. Second, while spending on robots is significantly correlated with the Communist Party membership status of the firm's chief executive officer, a firm's spending on general machinery is not. Third, the role of labor costs is mixed. On the one hand, wage costs have a larger impact on the use of general machinery than on the use of robots; on the other hand, worker turnover appears more important for the use of robots. Finally, replacing manual tasks is more important in explaining robot usage than general machinery usage. As reported in column 4, these differences are not always significant but are large in magnitude, suggesting that it is valuable for future research to study how different dimensions of labor costs and job task characteristics affect the use of robots as opposed to general machinery.

Conclusions

In this paper, we have sought to describe some key patterns in the rise of robots in China. At the aggregate level, the rise of robots has accompanied a decline in the growth of the working-age population and an increase in wages, suggesting that the rising cost of labor is one underlying driver of robot usage in China. Because China is a global leader in the production and consumption of automotive and electronics, the two leading industries in robot adoption, China probably will play an even more important role in the robot market in the future. The Chinese government's industrial policies are also likely to affect both robot adoption and production.

Using the China Employer-Employee Survey (CEES) data, we further provide firm-level evidence of the rise of robots in Chinese manufacturing firms. We believe that the evidence we have found on the roles of government and the market in driving the adoption of robot technology is particularly important. These analyses are some initial steps towards understanding the causes and consequences of the increasing use of robots in Chinese manufacturing. Such consequences include effects on firm productivity, complementarity/substitution between humans and robots, and other labor market outcomes.

At this stage, the threat of job replacement is not a high-priority concern in the mind of China's government or its citizens. Government policies are motivated by the challenges of labor costs and labor shortage, as well as the imperative to lead a new wave of Industrial Revolution. For employers, the labor force challenges are indeed important considerations for robot adoption, as shown by our analysis. For employees, the high voluntary turnover rates and the lack of strong and independent unions may partly contribute to their tolerance of robot adoption. It is conceivable, however, that the short-run consequences are different from those in the long run. We hope to make further progress on these questions by continuing to follow China's manufacturing firms.

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