研究报告 Research Report
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中国有色金属 China Non-ferrous Metals

机器人专题系列（四）：电机驱动勇立潮头
Special Theme on Robots (IV)

观点聚焦 Investment Focus

股票名称	评级	股票名称	评级
紫金矿业	Outperform	赤峰黄金	Outperform
天齐锂业	Outperform	川能动力	Outperform
赣锋锂业	Outperform	银泰黄金	Outperform
华友钴业	Outperform	驰宏锌锗	Outperform
洛阳钼业	Outperform	盛屯矿业	Outperform
山东黄金	Outperform	锡业股份	Outperform
石英股份	Outperform	立中集团	Outperform
天华超净	Outperform	安宁股份	Outperform
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中矿资源	Outperform	甬金股份	Outperform
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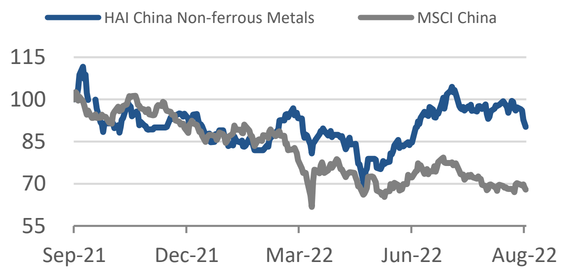

资料来源：Factset, HTI

Related Reports
机器人专题系列（三）（Special Theme on Robots (Ⅲ)）(28 Aug 2022)
海外龙头铜企 2022H1 产量同降 4%，连续下修全年产量指引（The output of overseas leading copper enterprises decreased by 4% in 2022H1, and the annual output guideline was continuously revised）(23 Aug 2022)
海外锂企 22Q2 经营情况梳理——售价持续上修，扩产加速进行中（Overseas Lithium Enterprises 2Q22 Review——Sales Price Increase with Capacity Expansion Accelerated）(21 Aug 2022)

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(Please see APPENDIX 1 for English summary)

本专题系列报告聚焦于机器人领域，旨在介绍机器人驱动系统搭载的常见电机，分析其各自特点及使用场景，探索未来机器人电机驱动更多自由度的实现。

机器人关节的运转在灵活度、可靠性、速度、形态方面均对驱动电机提出较高要求。伺服电机凭借较高的稳定性和较强的的调速、过载能力成为机器人驱动方式的不二选择，且其具备多种应用场景。交流伺服电机，凭借速度高、惯量小、转动平滑、力矩稳定等特点，用于对位置，控制精度，速度和力矩有比较高要求的需要，如印刷设备，激光加工，机器人，机床设备，机械手，自动化生产线等；直流伺服电机，具备结构简单、运行可靠、维护方便、运行效率高、无励磁损耗以及调速性能好的特点，在各种精度高的场合日益普及，如医疗器械、化工、机器人等。步进电机没有电刷、维护方便、寿命长，容易控制，适合要求运行平稳、低噪音、响应快、使用寿命长、高输出扭矩的应用场合，如工业控制系统、办公自动化、机器人等领域。

电机性能的差异直接影响机器人的行动灵活度和工作稳定性。机器人的关节驱动离不开伺服系统，其自由度实现越多，所需使用的伺服电机数量越多。优必选 Walker X 机器人高度模仿人的身体结构，41 个高性能纯电机伺服驱动关节，其中腿部 12 个，臂部 14 个，手部 12 个，颈部 3 个，能实现 3km/h 的最大行走速度，具备不平整地面平稳行走以及结构化地形行走能力，满足不同家庭场景的需要。特斯拉 Optimus 机器人搭载永磁同步电机，体积小效率高，但容易退磁，成本较高。拥有多达 40 个机电一体化的执行器，其中手臂 12 个、脖子 2 个、躯干 2 个、手部 12 个和腿部 12 个，可灵活完成各种人类动作，行走可做到稳中有速。

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1.电机

机器人电动伺服驱动系统是利用各种电动机产生的力矩和力，直接或间接地驱动机器人本体以获得机器人的各种运动的执行机构。

控制用电机是电气伺服控制系统的动力部件。它是将电能转换为机械能的一种能量转换装置。机电一体化产品中常用的控制用电机是指能提供正确运动或较复杂动作的伺服电机。

1.1 机器人电机须符合的主要要求

机器人关节的运转对驱动电机提出了较高要求，在灵活度上，要求其有最大功率质量比和扭矩惯量比、高起动转矩、低惯量；在性能上，伺服电动机须有较高的可靠性、稳定性，同时需能快速响应，具有较高的可靠性和稳定性；在动作上，能够控制特性的连续性和直线性；在速度上，要求较宽广且平滑的调速范围；在形态上，体积小、质量小、轴向尺寸短，且能经受得起苛刻的运行条件。

1.2 机器人驱动系统中常用的电机

机器人驱动系统常采用的电机大致可细分为以下几种：直流伺服电机(DC Servo Motor)、交流伺服电机(AC Servo Motor)、步进电机（Stepping Motor）。

图1 机器人常用电机类型

资料来源：海通国际

1.2.1 直流伺服电动机

直流伺服电动机，分为有刷直流伺服电机和无刷直流伺服电机。有刷直流伺服电机，优点是成本低，结构简单，启动转矩大，速度调节范围宽，控制容易，维护方便。缺点是会产生电磁干扰，对环境有要求。无刷直流伺服电机，具备体积小，重量轻，出力大，转动平滑，力矩稳定，高速且灵敏等优势，容易实现智能化，其电子换相方式灵活，可以方波换相或正弦波换相。电机免维护，不存在碳刷损耗的情况，效率很高，运行温度低，不易产生火花，噪音小，电磁辐射小，寿命相对较长。

应用场景方面，有刷直流伺服电机由于其成本较低，可用于对成本敏感的普通工业和民用场合。无刷直流伺服电机凭借其结构简单、运行可靠且效率高、调速性能好等特点，适用于各种对精度要求高的场合。

1.2.2 交流伺服电动机

交流伺服电动机，包括同步型交流伺服电动机及异步型交流伺服电动机等。异步型交流伺服电动机有三相和单相之分，通常多用鼠笼式三相感应电动机，主要为了使伺服电动机具有较宽的调速范围和快速响应的性能。其优点为结构简单，质量轻，噪声小，省去了昂贵的永磁体，价格相对便宜。缺点为难以实现平滑调整速度，控制系统成本高。同步型交流伺服电动机的复杂程度介于感应电动机与直流电动机二者之间。其定子装有对称三相绕组，转子由绕组形成的电磁铁构成，根据结构不同分为电磁式及非电磁式两大类。其无需励磁电流，没有励磁损耗，提高了电动机的效率和功率密度。

应用场景方面，交流伺服电动机凭借其速度高、惯量小、转动平滑、力矩稳定等特点，多用于如印刷设备，激光加工，机器人，机床设备，机械手，自动化生产线等对位置、控制精度、速度、力矩有较高要求的领域。

1.2.3 步进电动机

步进电动机，将电脉冲信号转变为角位移或线位移的开环控制元件，包括永磁式(PM)、反应式(VR)和混合式(HB)。反应式步进一般为三相，可实现大转矩输出，步进角一般为 1.5 度，但噪声大、振动幅度大，已在 80 年代被欧美等发达国家淘汰；混合式步进是指混合了永磁式和反应式的优点，分为两相、三相和五相，是工业运动控制运用最常见的电机。当步进驱动器接收到一个脉冲信号，就会驱动步进电机按设定的方向转动固定角度。

步进电机没有电刷、维护方便、寿命长，停止、正转、反转容易控制；控制精度由相数、拍数决定；低速时易出现低频振动现象，运转平稳性不足；输出力矩随转速升高而下降，一般不具备过载能力；加速性能欠佳，不适用于快速启动场合。其广泛应用于 ATM 机、喷绘机、刻字机、写真机、喷涂设备、医疗仪器及设备、计算机外设及海量存储设备、精密仪器、工业控制系统、办公自动化、机器人等领域，特别适合要求运行平稳、低噪音、响应快、使用寿命长、高输出扭矩的应用场合。

图2 电机类型、特点、原理、控制方式

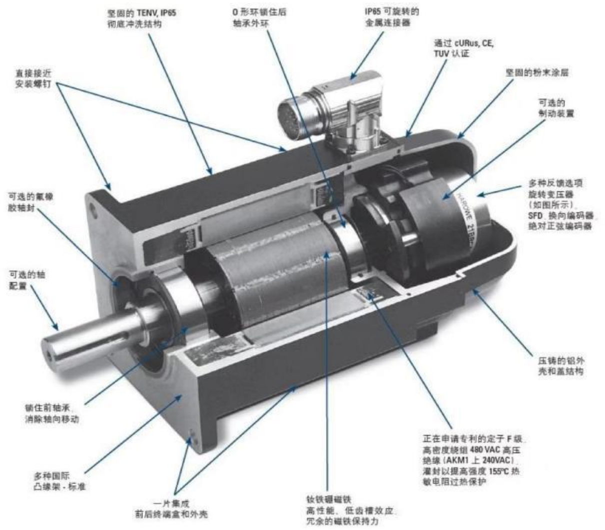
电机类型	主要特点	构造与工作原理	控制方式
直流伺服电机	只要接通直流电即可工作，控制简单； 启动转矩大、体积小、转速和转矩容易控制、效率高，需要维护和更换电刷。	由永磁体定子、线圈转子、电刷和换向器构成。通过电刷和换向器使电流方向不断随着转子的转动角度而改变，实现连续旋转运动。	主要有两种：电枢电压控制、励磁磁场控制。转速控制采用电压控制方式。转矩控制采用电流控制方式。
交流伺服电机	发热少，高速控制，高精确度位置控制。 运行平稳、噪音小。 没有电刷和换向器、不需维持。 驱动电路复杂。	按结构分为同步电机和异步电机，转子是由永磁体构成的为同步电机，转子是由绕组形成的电磁铁构成的为异步电机。无刷直流电机，结构与同步电机相同，特性与直流电机相同。	分为电压控制和频率控制两种方式。异步电机通常采用电压控制方式。
步进电机	直接用数字信号进行控制，与计算机的接口比较容易； 没有电刷、维护方便、寿命长； 启动、停止、正转、反转容易控制。 能量转换效率低，易失步。	按产生转矩的方式可分为永磁体式（PM），可变磁阻式（VR），和混合式（HB）。PM 式产生的转矩较小，多用于计算机外围设备。HB 式能够产生较大转矩，因此应用最广。	单相励磁：精度高，但易失步。 双相励磁：输出转矩大，转子过冲小，常用方式，但效率低。 单-双相励磁：分辨率高，运转平稳。

资料来源：同心制造网，海通国际

图3 24/48/72VDC 低压直流伺服电机图

资料来源：中国制造网，海通国际

图4 交流伺服电机组成及结构图



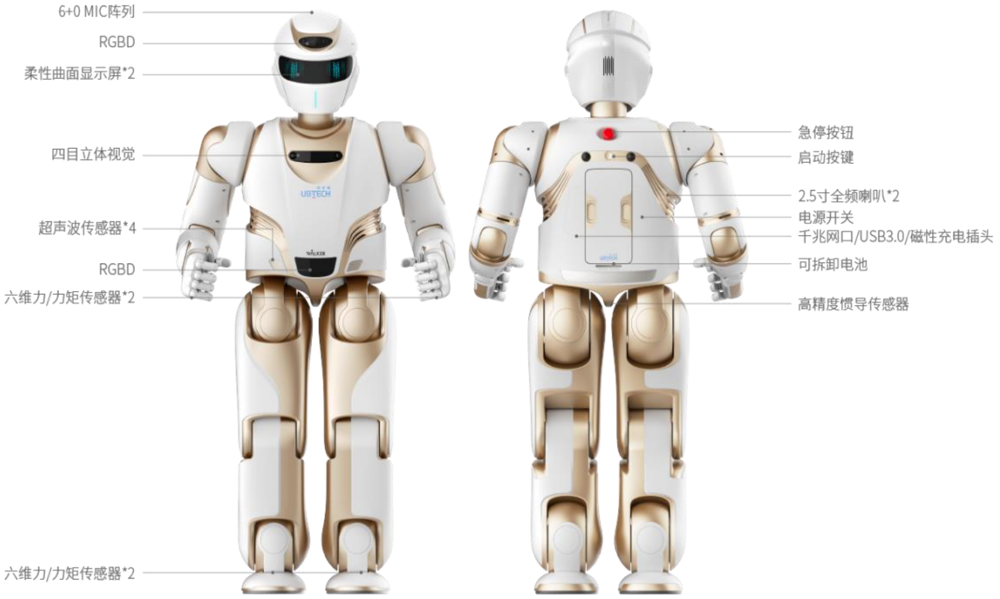
资料来源：电工之家，海通国际

1.3 纯电机驱动的机器人

1.3.1 优必选 Walker X 机器人

Walker X 高度模仿人的身体结构，身高 1.3 米，体重 63 公斤，41 个高性能伺服驱动关节，面部 160°环绕 4.6K 高清双柔性曲面屏。整体外部光滑圆润，没有明显的棱角，关节部位没有外露的机械限位结构，非常符合其家庭服务的定位。此外，Walker X 具备开放、灵活、丰富、便捷的 AIoT 接口，能够依据用户习惯和场景，自主控制灯光、冰箱等常见的 AIoT 设备，全方位满足智能家具场景的应用。

图5 优必选 WalkerX 机器人



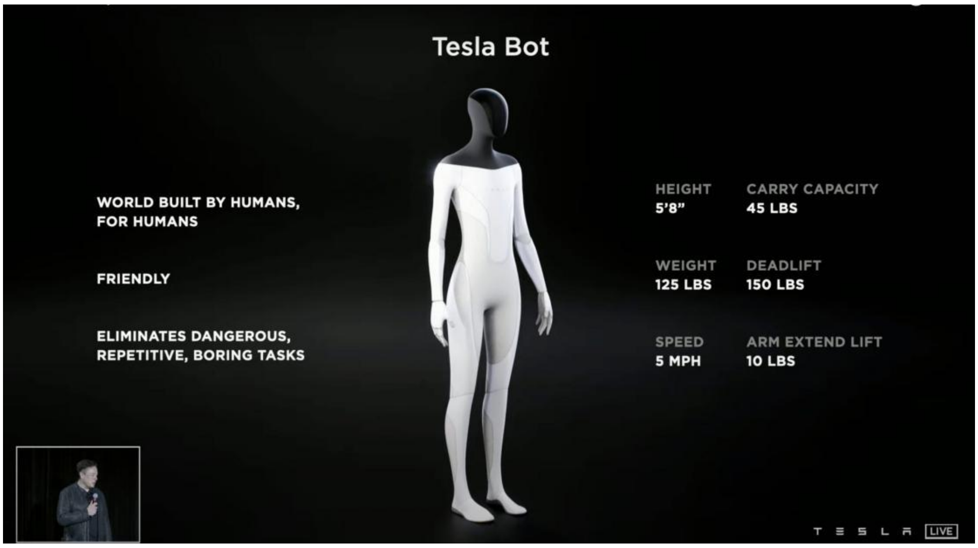
资料来源：优必选官网，海通国际

运动控制方面，硬件上，Walker X 采用纯电机伺服，凭借 41 个高性能伺服驱动关节实现类人步态行走，其中腿部 12 个，臂部 14 个，手部 12 个，颈部 3 个。软件上，Walker X 能实现 3km/h 的最大行走速度，虽然速度不快，但能精准地控制运动的幅度和角度，具备在碎石地、草坪等不平整地面平稳行走以及斜坡、楼梯等结构化地形行走的能力，以满足不同家庭场景的需要。另外，内置的行走平衡控制系统也使其能够在单腿站立或行走时抵抗外来干扰，落足稳定柔顺，全身可背 10kg 重物或双手负载 3kg 重物行走，拥有极强的稳定性。

1.3.2 特斯拉 Optimus 机器人

特斯拉机器人身高 5 英尺 8 寸，重量 125 磅，时速 5 英里，具有和人差不多的身高、体重和行走速度。拥有多达 40 个机电一体化的执行器，其中手臂 12 个、脖子 2 个、躯干 2 个、手部 12 个和腿部 12 个一体化电机的执行器机构，意味着可以灵活完成各种人类动作。由此可见，机器人系统中最重要的运动性能靠的是电机执行器的负载能力和响应速度，而且随着功能增加和动作的丰富，需要更多大小不一、性能不同的电机一体化执行器。

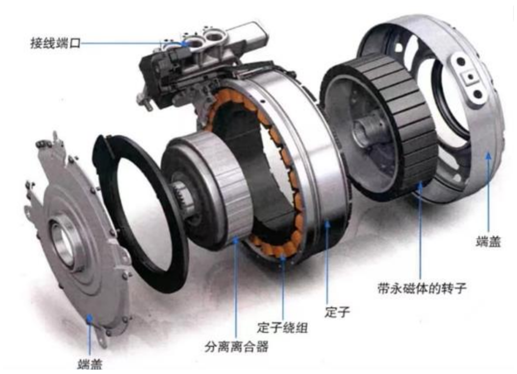
图6 特斯拉 Optimus 机器人



资料来源：特斯拉，海通国际

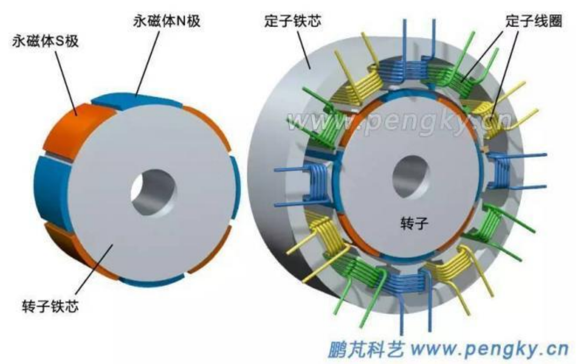
特斯拉机器人搭载永磁同步电机，体积小效率高，但容易退磁，成本较高。电机主要由定子、转子以及机械结构组成。永磁同步电机指的是定子上的线圈通电后产生的磁场能带动永磁体（转子）进行同步旋转，转子的转速也能够与旋转磁场的转速相同，不容易造成转速损耗。优点是体积小，效率高，但是一旦速度增加，永磁体产生反电势，导致高温，强震动就容易退磁。因此不适合在高速下使用。此外，永磁同步电机主要用稀土中的高性能钕铁硼永磁材料，成本较高。

图7 永磁同步电机构造图



资料来源：搜狐汽车，海通国际

图8 永磁同步电机的定子和转子构造图



资料来源：鹏芃科艺，海通国际

特斯拉在自动驾驶就研发了 IPM-SynRM，是内置永磁体的同步磁阻电机。永磁同步电机不适合在高速下使用。大型机械设备通常使用同步磁阻电机，在转子中嵌入铁，使转子处于低磁阻状态，适合高速运转。

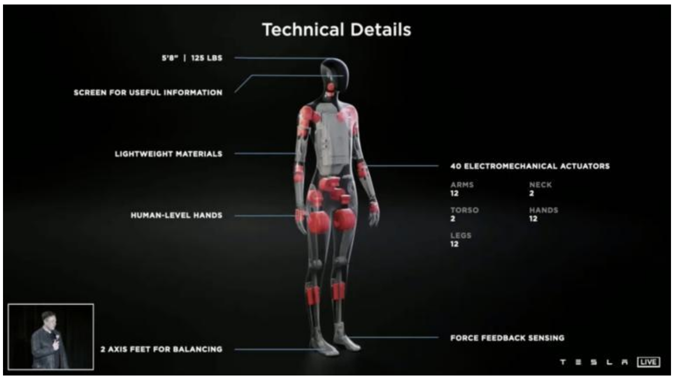
因此，特斯拉将这两种电机结合，永磁体代替铁嵌入转子，结合了共同的优点。在低速时它能作为永磁电机运转，在高速时又是一台磁阻电机，改善了电子线圈切割转子磁场的情况。

图9 Walker，WalkerX 和 Optimus 自由度数值对比

	腿	臂	手	颈部	总体
Walker	12	14	8	2	36
WalkerX	12	14	12	3	41
Optimus	12	12	12	2	40 （躯干 2 个）

资料来源：特斯拉，优必选官方，海通国际

图10 特斯拉 Optimus 公开概念细节图



资料来源：特斯拉，海通国际

APPENDIX 1

Summary

This series of reports focuses on the field of robotics, aiming to introduce the common motors equipped with robot drive systems, analyze their respective characteristics and usage scenarios, and explore the realization of more degrees of freedom for future robot motor drives.

The operation of robot joints places high demands on drive motors in terms of flexibility, reliability, speed, and form. Servo motors, with their high stability and strong speed regulation and overload capability, are the best choice for robot drives, and have a variety of application scenarios. AC servo motor, with its high speed, small inertia, smooth rotation, torque stability and other characteristics, for the position, control accuracy, speed and torque have relatively high requirements, such as printing equipment, laser processing, robotics, machine tool equipment, manipulators, automated production lines, etc.; DC servo motor, with a simple structure, reliable operation, easy maintenance, high operating efficiency, no excitation loss and speed regulation performance Good characteristics, in a variety of high precision occasions increasingly popular, such as medical equipment, chemical industry, robotics, etc. Stepper motors have no brushes, easy maintenance, long life, easy control, suitable for applications requiring smooth operation, low noise, fast response, long life, high output torque, such as industrial control systems, office automation, robotics and other fields.

The difference of motor performance directly affects the action flexibility and work stability of the robot. The robot's joint drive is inseparable from the servo system, and the more degrees of freedom it achieves, the more servo motors it needs to use. Ubiquity Walker X robot highly imitates the human body structure, with 41 high-performance pure motor servo-driven joints, including 12 for legs, 14 for arms, 12 for hands, and 3 for neck, which can achieve a maximum walking speed of 3km/h, with smooth walking on uneven ground and structured terrain walking ability to meet the needs of different family scenarios. Tesla Optimus robot is equipped with permanent magnet synchronous motor, small size and high efficiency, but easy to demagnetize and high cost. With as many as 40 mechatronic actuators, including 12 arms, 2 necks, 2 torsos, 12 hands and 12 legs, it can flexibly complete a variety of human actions and walk can be done at a steady speed.

附录 APPENDIX

重要信息披露

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优于大市，未来 12-18 个月内预期相对基准指数涨幅在 10%以上，基准定义如下

中性，未来 12-18 个月内预期相对基准指数变化不大，基准定义如下。根据 FINRA/NYSE 的评级分布规则，我们会将中性评级划入持有这一类别。

弱于大市，未来 12-18 个月内预期相对基准指数跌幅在 10%以上，基准定义如下

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Outperform: The stock's total return over the next 12-18 months is expected to exceed the return of its relevant broad market benchmark, as indicated below.

Neutral: The stock's total return over the next 12-18 months is expected to be in line with the return of its relevant broad market benchmark, as indicated below. For purposes only of FINRA/NYSE ratings distribution rules, our Neutral rating falls into a hold rating category.

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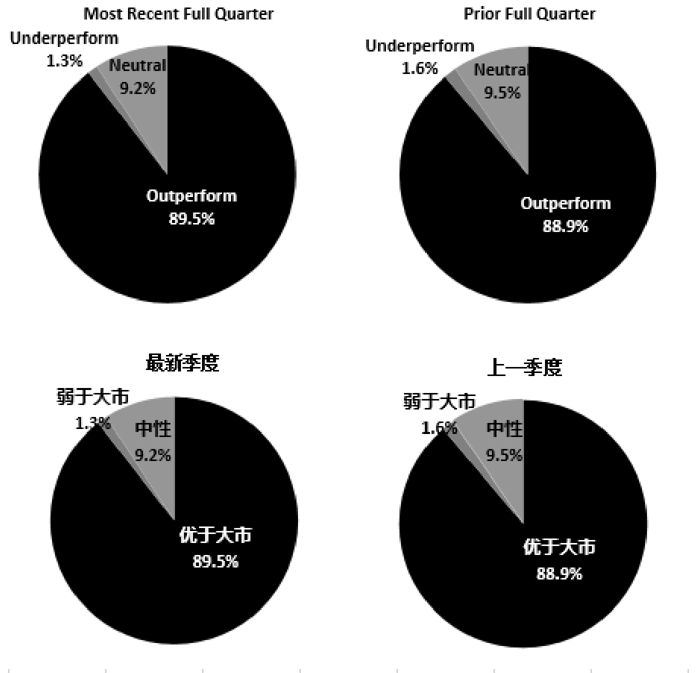
评级分布 Rating Distribution



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	优于大市	中性 (持有)	弱于大市
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投资银行客户*	5.9%	5.6%	5.0%

*在每个评级类别里投资银行客户所占的百分比。

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买入，未来 12-18 个月内预期相对基准指数涨幅在 10%以上，基准定义如下

中性，未来 12-18 个月内预期相对基准指数变化不大，基准定义如下。根据 FINRA/NYSE 的评级分布规则，我们会将中性评级划入持有这一类别。

卖出，未来 12-18 个月内预期相对基准指数跌幅在 10%以上，基准定义如下

各地股票基准指数：日本 – TOPIX, 韩国 – KOSPI, 台湾 – TAIEX, 印度 – Nifty100; 其他所有中国概念股 – MSCI China.

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*Percentage of investment banking clients in each rating category.

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SELL: The stock's total return over the next 12-18 months is expected to be below the return of its relevant broad market benchmark, as indicated below.

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